INVERSE DYNAMIC ANALYSIS OF ACL RECONSTRUCTED KNEE JOINT BIOMECHANICS DURING GAIT AND CYCLING USING OPENSIM

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ABSTRACT

Inverse Dynamic Analysis of ACL Reconstructed Knee Joint Biomechanics During Gait and Cycling Using OpenSim

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ACL (anterior cruciate ligament) injuries of the knee joint alter biomechanics and may cause abnormal loading conditions that place patients at a higher risk of developing osteoarthritis (OA). There are multiple types of ACL reconstruction (ACLR), but all types aim to restore anterior tibial translation and internal tibial rotation following surgery. Analyzing knee joint contact loads provide insight into the loading conditions following ACLR that may contribute to the long-term development of OA. Ten ACLR subjects, who underwent the same reconstruction, performed gait and cycling experiments while kinematic and kinetic data were collected. Inverse dynamic analyses were performed on processed data using OpenSim to calculate reconstructed and contralateral knee joint contact loads which were then compared between gait and cycling at both moderate and high resistances.

Significant differences were found between gait and cycling at either resistance for tibiofemoral (TF) compressive, anterior shear, lateral shear forces, and internal abduction and internal rotation moments for both ACLR and contralateral knees. Anterior shear force was largest for cycling at a high resistance, however, since the ACL provides a posterior restoring force and is more engaged at low flexion angles, adjusting for flexion angles when measuring AP shear forces should be considered. Overall, the calculated loading conditions suggest cycling provided better joint stability by limiting anterior tibial translation and internal tibial rotation compared to gait. The results suggest cycling is a better rehabilitation exercise to promote graft healing and limit abnormal loading conditions that increase the risk of developing OA.

Keywords: ACL reconstruction, osteoarthritis, knee joint contact, gait, cycling

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Chapter 1

1. INTRODUCTION

Anterior cruciate ligament (ACL) injuries of the knee have increased in recent years [1] and have led to a growing number of patients developing knee osteoarthritis (OA) [2, 3]. OA is an injury involving the articular cartilage and bone tissues that often results from abnormal biomechanical loading of the cartilage. ACL reconstruction (ACLR) is common post-injury to restore ligament and whole knee joint functionality (Fig. 1.1). Without surgery, patients lack knee stability and may experience abnormal biomechanics placing them at a higher risk for further injury and OA development [2, 4].

The two most common reconstruction techniques focus on anatomic attachment of the ACL's anteromedial (AM) and posterolateral (PM) bundles. The AM bundle engages during knee flexion and takes most of the load during anterior tibial translation at high flexion angles [5]. The PM bundle engages during knee extension and resists internal rotation at low flexion angles. A single-bundle (SB) reconstruction focuses on anatomic attachment of an AM bundle graft to restore anterior-posterior knee stability. A double-bundle (DB) reconstruction uses two grafts to recreate both bundles' functionality [6]. Another factor for reconstruction is attachment sites of the grafts. An anatomic reconstruction places the grafts at the center of their native attachment site whereas a non-anatomic reconstruction involves a more vertical graft position [7].

A SB reconstruction replaces only the AM bundle, and thus, is not considered as effective at resisting tibial rotation as the DB reconstruction [8]. However, a SB reconstruction is most common due to the technical difficulty of a DB reconstruction and lack of significant difference in knee range of motion and muscle activation [5, 8]. Additionally, anatomic reconstructions focus on placing the ACL graft at their native insertion points and are found to restore anterior and rotational stability better than non-anatomical reconstructions [7]. A reconstruction that restores ACL stability reduces abnormal knee biomechanics that could lead to irregular knee loading.

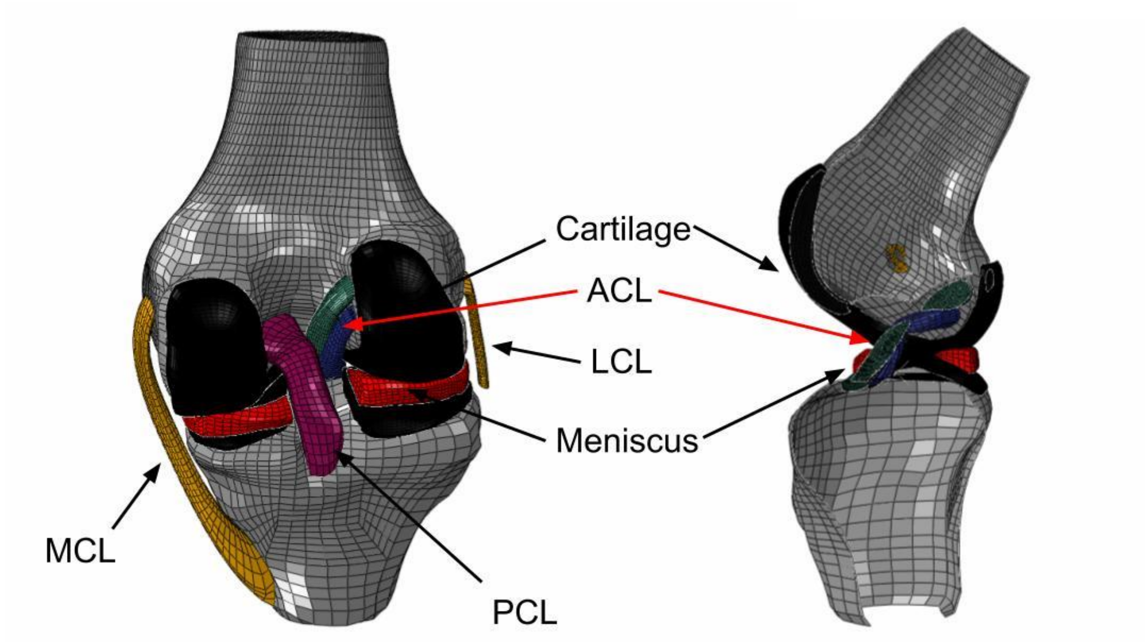

Figure 1.1: Posterior (left) and sagittal (right) views of an FE model of the knee joint, including the anterior (ACL), posterior (PCL), medial (MCL), and lateral (LCL) cruciate ligaments.

Following all types of reconstructions, knee joint instability has been observed for anterior tibial translations and internal-external (IE) rotations [1, 2, 4, 5, 6, 7, 9, 10, 11]. Tracking kinematics helps with calculating knee joint contact forces and moments to provide insight into the impact of reduced knee joint stability on articular cartilage loading. Knee joint contact tibiofemoral (TF) compressive, anterior-posterior (AP) shear, and medial-lateral (ML) shear forces estimate loading conditions of the knee joint. Knee joint contact moments, such as abduction-adduction (AA), provide insight into the cartilage and ligament loading of the knee. External knee adduction moments/internal knee abduction moments are linked with increased loading on the medial tibial cartilage and may increase OA risk in the medial compartment [3, 12]. Over time, the cyclic impact from abnormal gait loading on TF joint alignment contributes to tissue damage and, ultimately, are believed to increase incidence of OA [2, 3, 12].

Rehabilitation exercises are used to help stabilize the knee following ACL injury and reconstruction surgery. Previous studies found that ACLR knee kinematics vary during gait and running, primarily in regards to IE rotation [10, 11, 13, 14, 15]. Building the muscles surrounding the knee, such as the quadriceps and gastrocnemius, improves knee joint stability [16]. Cycling is recommended for OA at-risk populations due to reduced knee joint compressive forces that arise to cycling's status as a non-weight bearing exercises (i.e., the seat, and not the knees, supports the majority of body weight) [17]. In-vivo ACL strain studies in non-ACLR knees were found to be relatively low in cycling which may help maintain joint stability cycling during rehabilitation of ACL injuries and/or surgeries [18, 19]. Also, following reconstruction, the lack of anterior tibial displacement observed during cycling helps stabilize the joint [20]. However, reconstruction has been shown to not restore stability at high flexion angles which occur during cycling exercises [9].

Studies regarding non-ACLR knee kinematics have been tested for cycling, but not for ACLR patients specifically. Many gait and cycling studies have used in-vivo techniques to obtain knee joint loading, however, for at-risk populations, invasive methods such as these are not ideal [21, 22]. EMG-driven inverse dynamic (ID) analysis offers a non-invasive method for analyzing kinematics and kinetics of the knee joint as shown in previous gait studies [23] and has not been used for evaluating ACLR knee joint contact loads.

The long-term goal of this study is to provide evidence-based guidelines to recommend rehabilitation exercises for ACLR patients that promote graft healing and reduce the risk of OA development. In this study, focus was restricted to gait and cycling exercises. The main hypothesis was that knee joint contact loads (forces and moments) of ACLR patients would differ in gait and cycling exercises. Due to previous studies finding significant differences in knee joint kinematics of the reconstructed knee compared to the contralateral knee [13, 24, 14], a secondary hypothesis was that knee joint contact loads of ACLR patients would differ in the ACLR and contralateral knees. To address these hypotheses, the specific aims were to (1) conduct gait and cycling experiments with ACLR patients, (2) perform ID analysis to obtain knee joint contact loads, and (3) compare knee joint contact loads in the ACLR and contralateral knees in gait and cycling.

Chapter 2

2. METHODS

2.1 Participant Selection and Informed Consent

Protocols were approved by our Institutional Review Board and were designed to minimize risk to human participants. Ten participants (7 female, 3 male) who underwent ACL anatomic single bundle reconstruction with an autograft by a board certified orthopedic surgeon (Dr. Otto J. Schueckler) were tested 9-32 (21 ± 7.5) months post-op. Ages ranged between 18-45 (29.9 ± 10.8) years old and all participants were non-obese as classified by body mass index (BMI) (25.5 ± 3.35). Exclusion criteria included any history of cardiovascular, respiratory, or metabolic disease/complication, any substantial weight loss or weight gain in the previous 6 months, pre-existing conditions (other than ACLR) that may produce abnormal knee biomechanics (e.g. varus-valgus misalignment, other joint injuries), and women pregnant or trying to become pregnant.

After an initial telephone interview to discuss the study and participant eligibility, each interested participant visited the Human Motion Biomechanics (HMB) lab where the study was explained in more detail and informed consent was obtained. After obtaining informed consent, participants completed the Physical Activity Readiness Questionnaire (PAR-Q), Photographic Image Release Agreements, and Test Participant Information form. Body weight and height of each participant were recorded.

2.2 Equipment

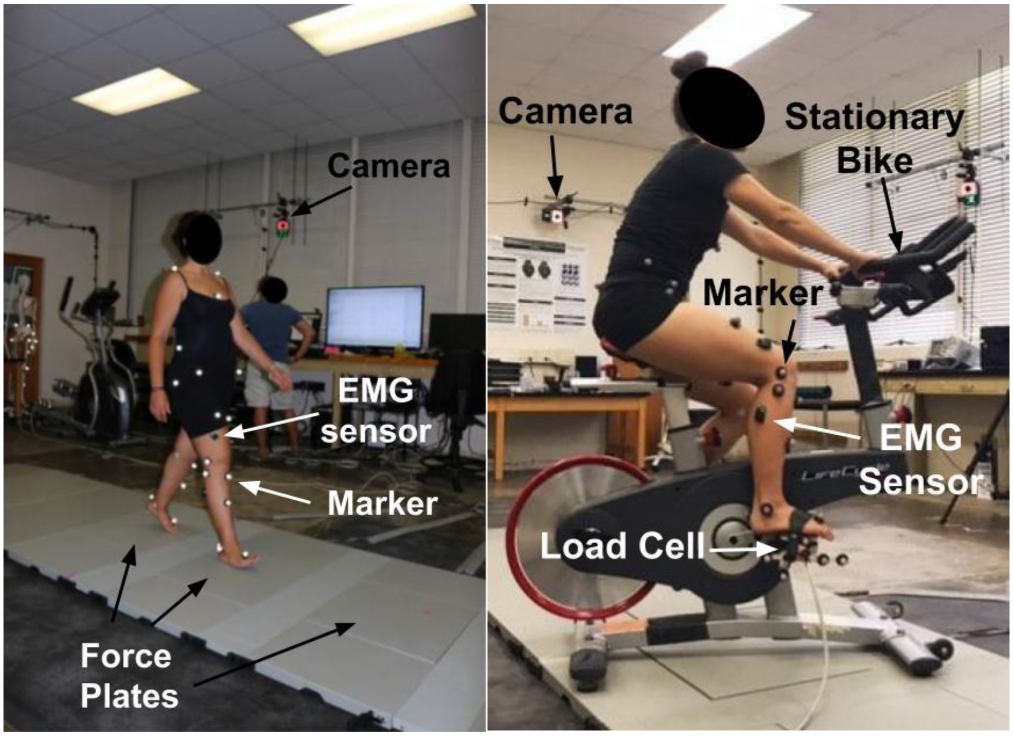

Figure 2.1: Equipment setup for gait (left) and cycling (right) experiments.

The HMB lab utilized a motion analysis system (Motion Analysis Corp. Santa Rosa, CA, USA) and peripheral equipment which consisted of the following (Fig. 2.1): (1) twelve (6 Owl, 3 Osprey, 2 Kestrel, 1 Eagle) digital cameras (Motion Analysis); (2) Cortex software (Version 7.01, Motion Analysis) for calibration, setup, data collection, and post-processing; (3) 20 mm retroreflective markers (Motion Analysis); (4) 4 ground forces plates (Accugait, AMTI, Watertown, MA, USA) that measured time-dependent ground reaction forces and moments aligned in a walkway; (5) a stationary bike (Lifecycle GX, Life Fitness, Schiller Park, IL, USA) retrofitted with custom pedals containing 6-axis load cells (AMTI, Watertown, MA, USA) with markers attached to track pedal orientation and relate local load cell coordinate system to the Cortex coordinate system; and (6) 12 wireless EMG sensors (Trigno, Delsys, Natick, MA, USA). The cameras tracked marker trajectories within the capture volume and kinematic data were recorded in Cortex software at a frequency of 150 Hz. The kinetic data from the force plates for gait, and load cells for cycling, were captured at a frequency of 150 Hz and synchronized with kinematic data within Cortex. EMG data was collected at a frequency of 1925 Hz and synced using Cortex.

2.3 Experimental Protocol

Following informed consent, participants changed into compression gear. Areas of the skin where markers/electrodes were placed were cleaned with rubbing alcohol. For 7 participants, wireless EMG sensors were positioned on the gastrocnemius, vastus lateralis, vastus medialis, rectus femoris, biceps femoris, and anterior tibialis muscles of each leg. The remaining 3 participants were part of an introductory study, and thus only had EMG sensors placed on one leg instead of both legs. An enhanced Helen Hayes marker set with 32 retroreflective markers were placed on anatomical landmarks to track kinematics (Appendix H). A static pose capture (Fig. 2.2) of the participant was collected to obtain reference knee angles and to perform scaling in OpenSim (Stanford University, Palo Alto, CA, USA). Medial markers of the knees and ankles and the top head marker were removed following static capture. For gait, participants performed 3 trials in each direction walking across the force plates at self-selected walking speeds. For cycling, participants pedaled at a cadence of 70 revolutions per minute (RPM) at moderate (10) and high (15) machine resistance levels for 30 seconds.

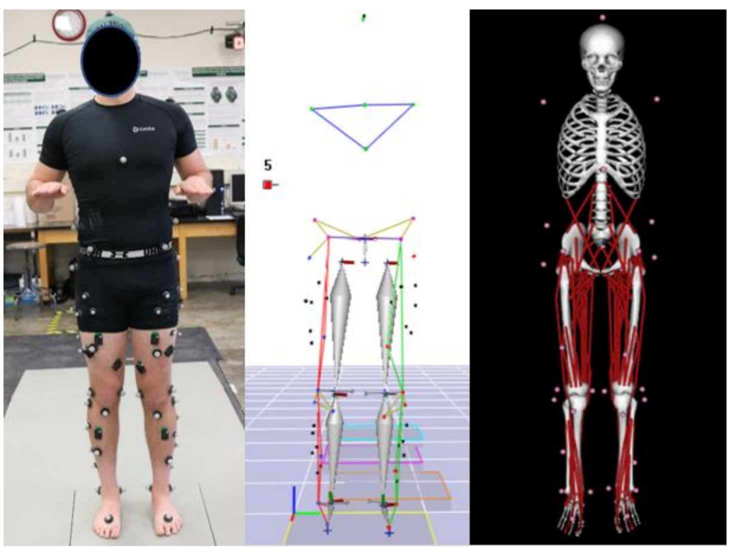

Figure 2.2: Participant standing in static pose in the lab (left), processed static pose in Cortex (Motion Analysis) (middle), and scaled participant in OpenSim (Stanford) (right).

2.4 Analysis

2.4.1 Kinematic and Kinetic Processing

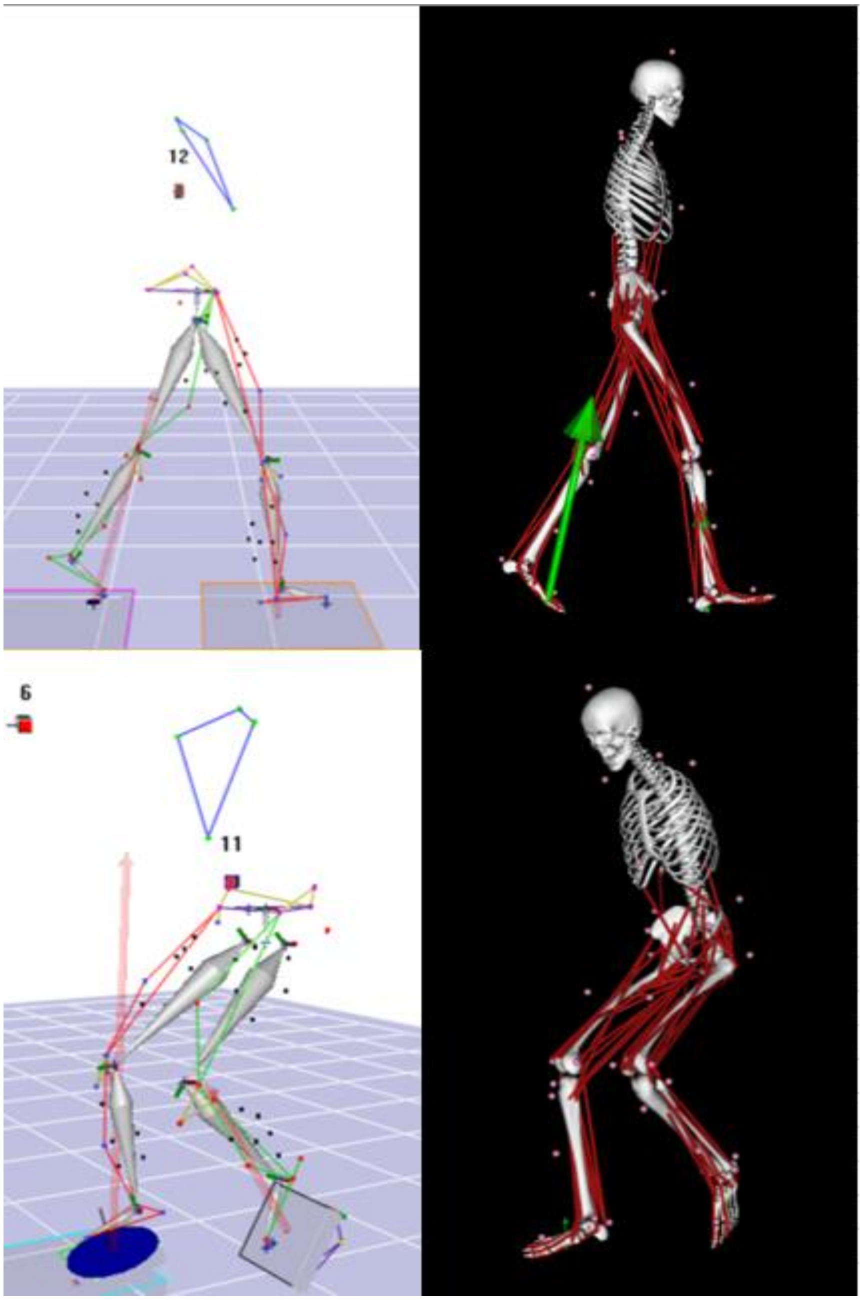

Figure 2.3: Gait (top) and cycling (bottom) simulations in Cortex (Motion Analysis) (left) and OpenSim (Stanford) (right).

The static, 3 gait, and 3 cycling trials were processed using Cortex to obtain marker trajectories (i.e. kinematic data) (Fig. 2.3). Kinematic data were filtered using a 4th order

Butterworth filter at a cutoff frequency of 6 Hz. Kinematic and kinetic data were exported to Matlab (MathWorks, Natick, MA, USA) for formatting to use in OpenSim (Stanford University, Palo Alto, CA, USA). In Matlab, kinetic data were filtered using a 4^{th} order Butterworth filter at a cutoff frequency of 6 Hz and EMG data were filtered using a bandpass filter of 20Hz to 450Hz [25].

2.4.2 OpenSim Processing

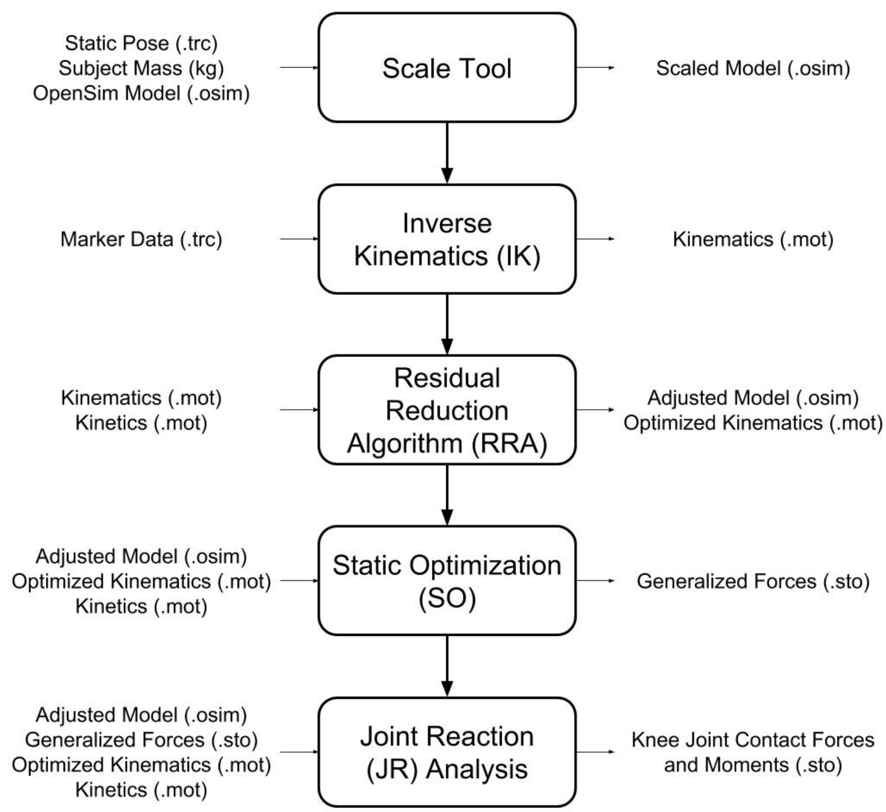

Figure 2.4: Flowchart of the analysis performed in OpenSim.

An OpenSim musculoskeletal model, with 1-degree of freedom (flexion) at the knee, was scaled to each participant using the static trial data [26] (Fig. 2.4). Dynamic trial kinematic data were inputted into the Inverse Kinematics (IK) tool to output joint kinematics. Those results were used with kinetic data to run Residual Reduction Algorithm (RRA). The RRA tool uses Newton's Second Law to equate external forces with the motion of the model to then output a model with corrected segment masses, adjusted torso mass center, and optimized kinematics; RRA adds pelvic residual forces then optimizes kinematics to minimize these residuals. For cycling, the forces from the handlebars and seat were not measured, thus to ensure RRA was able to run, the pelvis translational coordinates were locked after running IK to model the pelvis as a ball and socket joint. The adjusted model, optimized kinematics, and kinetic data were all used to run the Static Optimization (SO) tool. SO used the model's motion to solve for unknown generalized forces (i.e. joint forces and moments) and outputs the estimated forces. Those results were then used with the other inputs to conduct Joint Reaction (JR) analysis which produces the model's joint contact forces and moments. See Appendix A for further descriptions of OpenSim tools.

Results were trimmed to 1 full gait cycle (0% = 1st heel strike, 100% = 2nd heel strike) or crank revolution (Fig. 2.5) (0% = 1st top dead center (0 deg.), 100% = 2nd top dead center (360 deg.)). A Matlab code was used to average each participant's 3 trials for each leg. The average knee joint contact force and moments were normalized by body weight (BW; N) and by mass multiplied by height (kg-m), respectively [27]. TF compressive, anterior shear, and medial shear forces, as well as abduction, internal, and flexion moments, were defined as positive. Power output calculations were performed for each cycling trial based on a nearly constant cadence of 70 RPM (Appendix I).

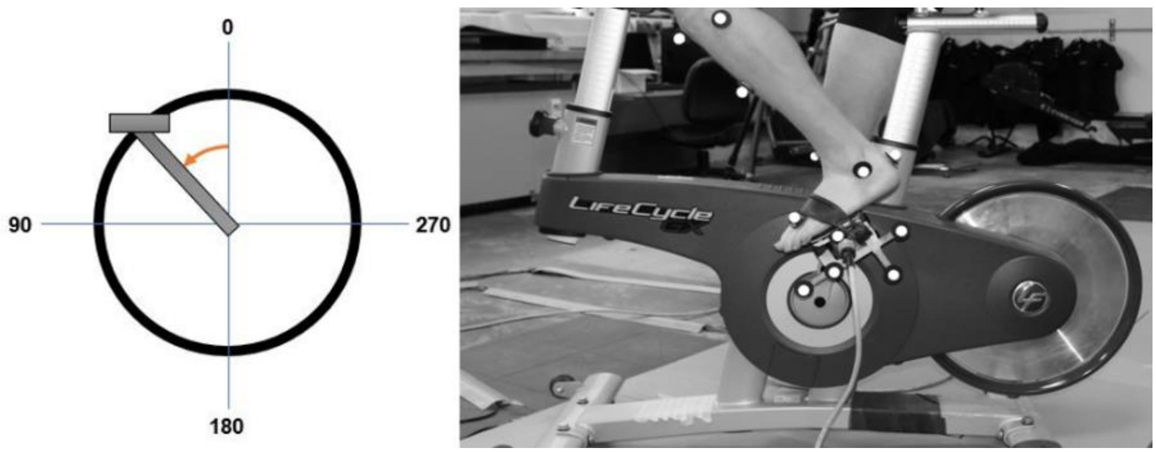

Figure 2.5*:* The coordinate system (left) used to define the crank angle of the stationary bike (right).

2.4.3 Statistical Analysis

Two-way repeated measures ANOVA and Tukey post-hoc tests were conducted to analyze the effect of knee status (reconstructed/contralateral) and exercise type (gait/moderate cycling/strenuous cycling) on the minimum and maximum knee joint contact forces and moments. The positive direction of each force and moment accounts for a specific direction, and thus, determining the minimum and maximum of each load ensures the peak of each load is analyzed. Significance for all tests was defined by $p<0.05$.

Chapter 3

3. RESULTS

Self-selected walking speeds were 1.27 ± 0.13 m/s. Cycling at moderate and high resistances produced power levels of 28.11 ± 6.55 Watts and 88.01 ± 9.96 Watts, respectively (Appendix I).

TF compressive ($p < 0.001$), minimum AP shear ($p < 0.001$), and minimum ML shear ($p < 0.001$) forces were significantly different for gait compared to cycling at either resistance (Fig. 3.1). Maximum AP shear force was significantly different for cycling at a high resistance compared to gait (C2 ACLR vs G ACLR: $p = 0.005$; C2 ACLR vs G contralateral: $p = 0.004$; C2 contralateral vs G ACLR: $p = 0.001$; C2 contralateral vs G contralateral: $p = 0.001$) and cycling at a moderate resistance (C2 ACLR vs C1 ACLR: $p = 0.001$; C2 ACLR vs C1 contralateral: $p = 0.001$; C2 contralateral vs C1 ACLR: $p < 0.001$; C2 contralateral vs C1 contralateral: $p < 0.001$). Maximum ML shear force was significantly different for the ACLR knee during gait compared to cycling at a moderate resistance for either knee (ACLR: $p = 0.009$; Contralateral: $p = 0.011$). Similar loads were found between the ACLR and contralateral knees for the maximum and minimum of all other knee joint contact forces. The results from the post-hoc Tukey tests following the two-way repeated measures ANOVA tests are summarized in Appendix C. The average and standard deviation of the maximum and minimum values of each force is summarized in Table B-1 and Table B-2, respectively.

Maximum AA ($p < 0.001$) and minimum IE ($p < 0.001$) moments were significantly different for gait compared to cycling at either resistance (Fig. 3.2). Maximum IE moment was significantly different for cycling at a moderate resistance compared to gait (C1 ACLR vs G ACLR: $p = 0.019$; C1 ACLR vs G contralateral: $p = 0.003$; C1 contralateral vs G ACLR: $p = 0.033$; C1 contralateral vs G contralateral: $p = 0.006$) and cycling at a high resistance (C1 ACLR vs C2 ACLR: $p = 0.011$; C1 ACLR vs C2 contralateral: $p = 0.001$; C1 contralateral vs C2 ACLR: $p = 0.020$; C1 contralateral vs C2 contralateral: $p = 0.003$).

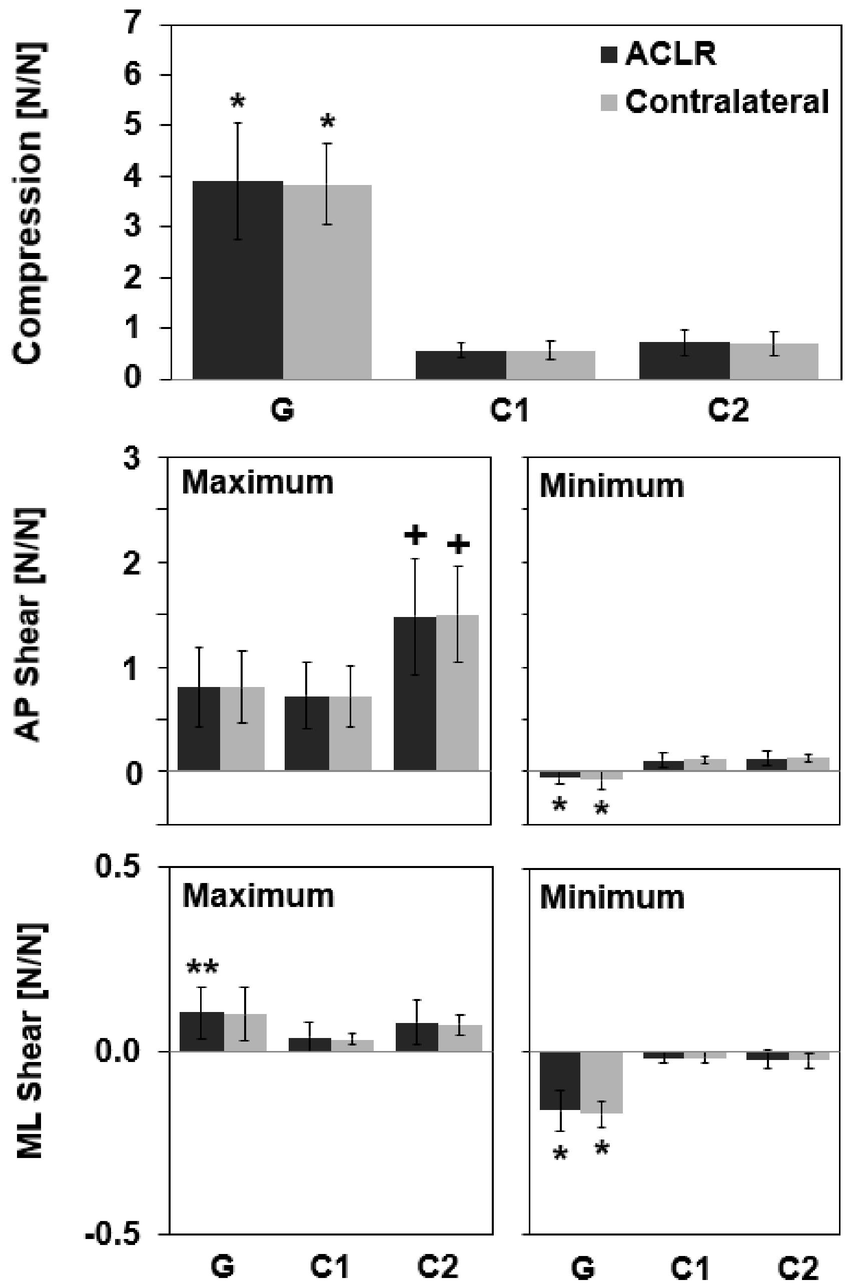

Figure 3.1: Comparison of knee joint contact forces between gait (G), cycling at moderate resistance (C1), and cycling at high resistance (C2) for ACL reconstructed (ACLR) and contralateral knees. Positive AP and ML shear forces are anteriorly and medially directed, respectively. * = significantly different than both ACLR and contralateral results for C1 and C2 ($p<0.05$); + = significantly different than both ACLR and contralateral results for G and C1 ($p<0.05$); ** = significantly different from ACLR and contralateral results for C1 ($p<0.05$).

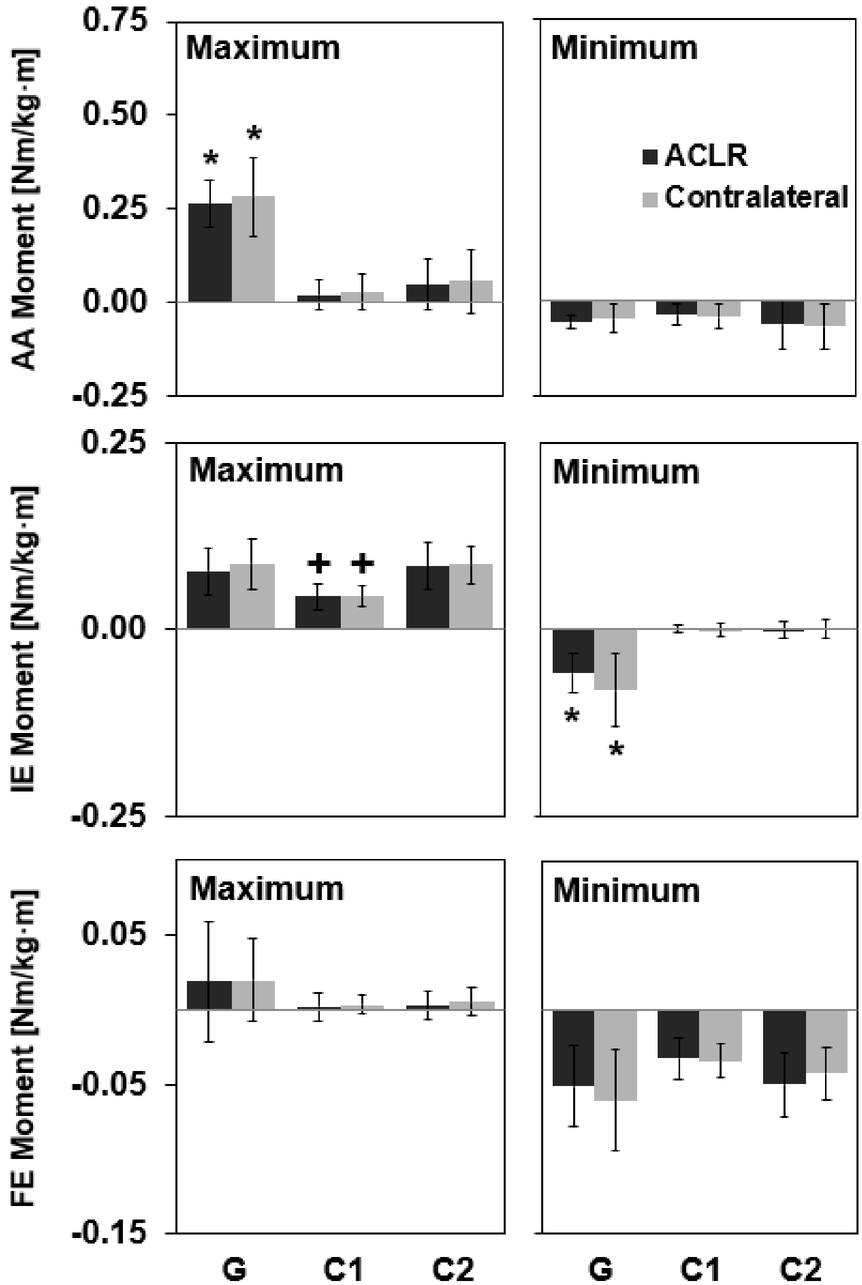

Figure 3.2: Comparison of knee joint contact moments between gait (G), cycling at moderate resistance (C1), and cycling at high resistance (C2) for ACL reconstructed (ACLR) and contralateral knees. Positive AA, IE, and FE are abduction, internal, and flexion directed moments. * = significantly different than both ACLR and contralateral results for C1 and C2 ($p<0.05$); + = significantly different than both ACLR and contralateral results for G and C2 ($p<0.05$).

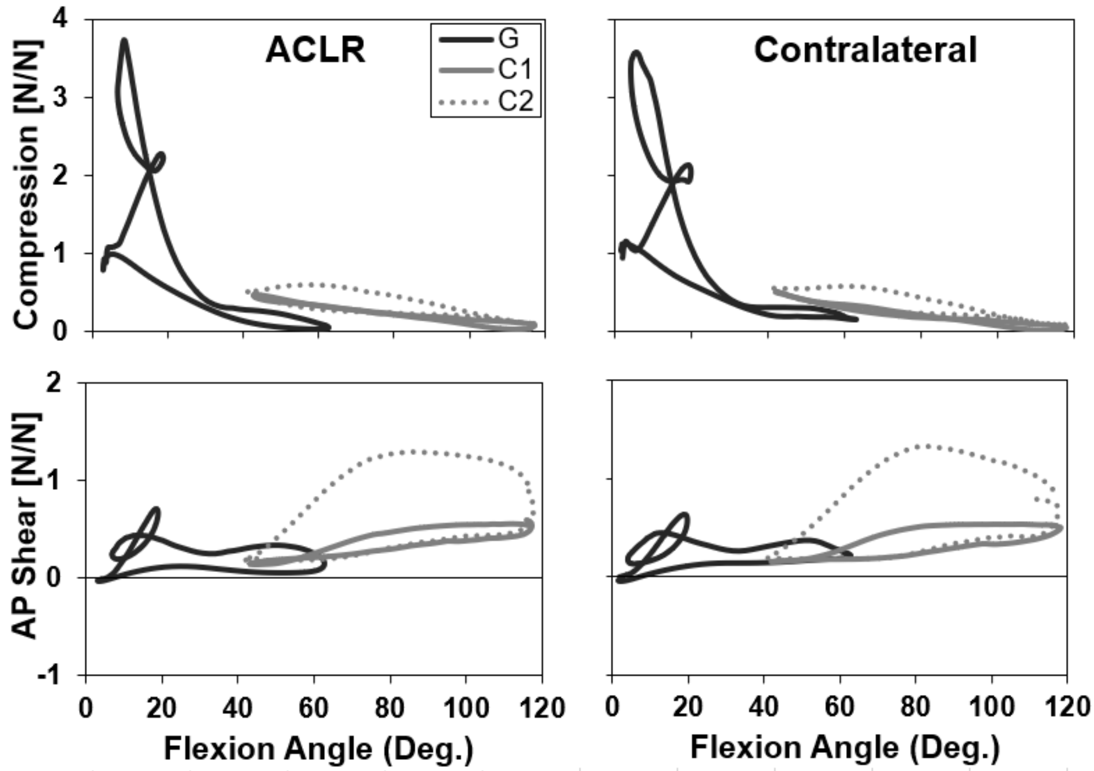

Figure 3.3: Knee flexion angle vs. TF compressive and AP shear force for gait (G), cycling at moderate resistance (C1), and cycling at high resistance (C2) for ACL reconstructed (ACLR) and contralateral knees. Positive AP shear is anteriorly directed.

A one-way ANOVA test comparing the ACLR and contralateral knees during gait at 1st flexion peak, minimum flexion angle, and 2nd flexion peak found no significant difference (Appendix E). Compressive force plotted against knee flexion angles found that peak compressive force during gait, cycling at a moderate power level, and cycling at a high power level for ACLR and contralateral knees occurred at 8.5, 5.6, 43.2, 42.3, 56.9, and 60.9 degrees, respectively (Fig. 3.3). Flexion angles at which maximum AP shear force occurred in the ACLR and contralateral knees during gait, cycling at a moderate power level, and cycling at a high power level, was 18.4, 19.2. 115.8, 107.6, 86.3, and 82.7 degrees, respectively. These results suggest that peak compressive and AP shear forces occur at lower flexion angles for gait compared to cycling at either resistance.

Chapter 4

4. DISCUSSION

The results from this study support the hypothesis that knee joint contact loads in ACLR patients differ in gait and cycling. Significantly different TF compressive, AP shear, and ML shear forces were found for gait compared to cycling. The results suggest that cycling, and possibly other non-weight bearing exercises, may limit abnormal knee cartilage loads and, thus, may be more ideal for limiting OA risk in ACL injured and reconstructed patients [23]. Cycling at either resistance reduced the TF compressive force compared to gait. The significantly larger laterally directed shear force in gait compared to cycling may place at-risk populations at a higher risk as well. AP shear force was largest in cycling at a high power level, however, since the ACL predominately applies a posteriorly directed shear force, if the shear force was adjusted for flexion angle, this result suggests lower ACL strain and anterior tibial translation during cycling [20].

Cycling power levels produced some variance in shear forces. The ACLR medially directed shear force was significantly higher during gait compared to cycling at a moderate power level for either knee. This was the only loading that found a significant difference between the ACLR and contralateral knees. The moderate power level also produced significantly lower IE rotation (internally directed) moment compared to gait and cycling at a high-power level. Higher power levels during cycling were found to produce larger anteriorly directed shear forces, compared to gait and cycling at a moderate power level. Lower anterior forces mean less anterior tibial displacement, less loading of the ACL, and more normal knee joint positioning. The impact of power levels on shear forces and moments shows power levels should be considered when designing a rehabilitation exercise program. A limitation of this study was the power output levels analyzed. These were low compared to power output of regular cycling exercise, and thus, lower forces were observed [22]. However, the resistances selected for this study were ideal to avoid excessive loading of the ACL.

Internal abduction moments and external rotation moments were significantly higher for gait than cycling at either resistance. Internal knee abduction moment helps estimate the medial to lateral cartilage loading, and thus, a large internal abduction moment is likely due to altered biomechanics that increase loading on the medial compartment and stretches ligaments on the lateral side that produce a restoring force. Studies have found that OA to be most common in the medial compartment for ACLR patients [3]. The larger external rotation moment found in gait shows less IE rotational stability compared to cycling. ACLR patients are found to have IE instability so it is ideal to limit IE moments. These results suggest making cycling a preferred exercise for limiting OA development and to increase knee joint stability.

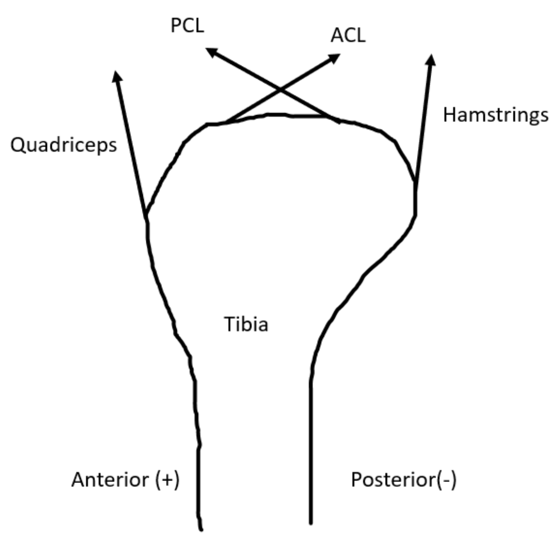

Figure 4.1: Sagittal plane diagram depicting the forces acting on the proximal tibia. Forces shown are due to the hamstrings, quadriceps, anterior cruciate ligament (ACL), and posterior cruciate ligament (PCL).

The peak TF compressive force in gait occurred at low flexion angles (Fig. 3.3) around heel-touch and before toe-off during the gait cycle. In this study, the posterior shear force observed only in gait occurred at low flexion angles which is where previous studies have found ACL strain to be the largest [16]. ACL injuries are thought to occur often at low flexion angles because the angle of the ACL is high relative to the tibia plateau, and thus a large ACL restraining force is needed to counter the anterior shear (Fig. 4.1). During cycling, in vivo studies of ACL strain found no significant difference in ACL strain with changes in power level or cadence and the overall mean peak strain value was low compared to other rehabilitation exercises [19]. Although this study found larger maximum AP shear forces for cycling at a high power level compared to gait, it is important to note that these peak values occurred at higher flexion angles, and at higher flexion angles the ACL is more aligned with the direction of the restoring posterior force. This entails that compared to gait, the ACL loads may have been substantially lower during cycling at a moderate power level and may have even been lower in cycling at a high power level. These results suggest that cycling requires a lower ACL restraining force making it an ideal rehabilitation exercise for ACLR participants as this is beneficial for graft healing. However, no analysis regarding ACL angles was performed in this study, thus further testing is needed to confirm that large AP shear forces at high flexion angles result in less ACL strain than small AP shear forces at low flexion angles.

This study was limited to flexion for its kinematic analysis during OpenSim due to the use of the one-degree of freedom model [28]. Previous studies also found knee flexion to be similar between the ACLR and contralateral knees [13]. However, a significant difference in IE rotation between ACLR and contralateral knees during stance phase was found, with most participants producing a more externally rotated tibia relative to the contralateral knee. Similar rotational offsets have been found in a variety of activities studies [24, 29, 4, 15] and combined knee valgus and internal rotation moments increase ACL strain [1], suggesting the rotational offset may cause degeneration of the cartilage. These findings were obtained with in vivo measurements and knee joint simulations. The results of this study are similar to those obtained using non-invasive methods, thus the novel methods used in this study show knee kinematic and kinetic data can be obtained non-invasively. The model used in this study is designed so that the small amount of axial rotation observed during joint flexion is used to help define the flexion angle, and thus, flexion angles outputted may include slight differences in knee rotations [30]. Future studies should use a more robust musculoskeletal model in OpenSim along with the methods developed from this study to analyze additional kinematic degrees of freedom at the knee. Recently developed OpenSim models that are designed for tasks involving high flexion angles [31] or analyze medial and lateral TF contact forces [32] should be considered. In addition, utilizing algorithms to correct for errors due to soft tissue artifact and crosstalk should be used to obtain more accurate estimates of AA and IE kinematics of ACLR patients.

A limitation of this study was the assumption that minimal pelvic residuals from RRA were ideal. For gait, these were close to zero, but not for cycling. A previous study measured handlebar loads on a treadmill and found those were comparable to minimized pelvic residuals [33]. Future work is being conducted to measured seat and handlebar forces during cycling and create handlebar and seat equivalent (HBSE) forces. The HBSE forces will then be used to validate the pelvic residuals obtained following RRA to ensure OpenSim produces realistic minimized pelvic residuals for cycling analyses. Overall, this study proved that calculating knee joint contact loads during cycling is possible in OpenSim and these methods may be utilized to study other possible rehabilitation exercises.

Static optimization limited this study due to its method of estimating muscle forces to calculate knee joint contact forces. Computed muscle control (CMC) is a similar tool found in OpenSim that can utilize EMG data when calculating knee joint forces. Only 7 out of the 10 subjects in this study had 6 EMG sensors on each leg, thus EMG-driven ID analysis could not be performed on all subjects. For the 7 subjects with EMG data, this analysis was performed, and a summary of the results can be found in Appendix D. Paired t-tests were conducted for all knee joint contact forces and moments to compare the use of SO versus CMC (Appendix F). SO and CMC produced significantly different results and this comparison is summarized in Appendix E.

Similar maximum and minimum values were found between the ACLR and contralateral knees for the majority of the loads analyzed in this study. This suggests that cycling may be a preferred exercise for not only ACLR participants, but for other populations that are at risk for developing knee OA.

Gait had higher compressive, posteriorly directed AP shear, and laterally directed ML shear forces, and abduction directed AA and externally directed IE moments. The TF compressive and ML shear forces as well as high AA moment may be contributing to the altered cartilage loading putting ACLR patients at risk for OA. The AP shear force and IE moment show signs of knee joint instability. These factors provide evidence towards using cycling as a rehabilitation and fitness-sustaining exercise. However, the power level for cycling was found to be significant for anteriorly directed AP shear and medially directed ML shear forces, and internally direction IE moment suggesting cycling at lower power levels should be considered when designing a rehabilitation exercise program for ACLR patients.

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APPENDIX A: OpenSim Tools

Scale Tool: A model with virtual markers is scaled using the measured distances between markers in static pose and the scale factors in the setup file (Fig. *2.2*). Scaling works by shifting the model to align the virtual markers with the experimental markers placed on anatomical positions. The distances between markers are used to scale each segment of the model. The participant's overall mass is inputted in the setup file and segment masses are distributed accordingly.

Inverse Kinematics (IK): The IK tool uses the experimental marker locations to compute the coordinate values (joint angles) at each time step. Marker errors are minimized using a weighted least squares problem. A coordinate file may be used to assist with calculations, however, for this study, no coordinate files were used during IK.

Residual Reduction Algorithm (RRA): RRA uses Newton's second law (Eq. A-1) to equate the results from IK with the inputted kinetics. This is done by using forward dynamics and adding 6 residuals at the pelvis (Eq. A-2) to determine mass distribution and optimize kinematics.

$$F = ma \qquad (A-1)$$

$$F + F_{res} = ma \qquad (A-2)$$

An actuators file, which contains the minimums and maximums of the model's muscles, is adjusted with each iteration of RRA to minimize pelvic residual forces. The outputted model has an adjusted torso mass center to account for the model "leaning" due to inaccuracies of weight distribution and torso geometries. Recommended mass changes are outputted but must be manually inputted into the model's segment properties. These mass adjustments are based on minimizing the F_y residual. RRA is considered completed when the mass adjustments are minimal, and the pelvic residual forces and moments are below 10 N and 50 Nm, respectively.

Static Optimization (SO): The Static Optimization tool uses the model's kinematics and kinetics to solve for the unknown forces (joint moments, muscle force, etc.) based on predefined muscle activation-to-force definitions (Eq. A-3, A-4, A-5).

$$\sum_{m=1}^{n}(a_m F_m^0) r_{m.j} = \tau_j \qquad (A-3)$$

$$\sum_{m=1}^{n}[a_m f(F_m^0, l_m, v_m)] r_{m.j} = \tau_j \qquad (A-4)$$

$$J = \sum_{m=1}^{n}(a_m)^p \qquad (A-5)$$

n = number of muscles in the model
a_m = activation level of muscle *m*
F_m^0 = maximum isometric force
l_m = muscle length
v_m = shortening velocity
$f(F_m^0, l_m, v_m)$ = force-length-velocity surface*
$r_{m,j}$ = moment arm about joint *j*
τ_j = generalized force acting about joint *j*
p = user-defined constant

Muscle activations are estimated based on published muscle activity for different body motions. The forces file containing the generalized forces is outputted from this tool then used to perform Joint Reaction analysis.

Joint Reaction (JR) Analysis: JR analysis uses all loads and model motion to calculate joint forces and moments between consecutive segments of the model. The reaction is assumed at the joint center of the proximal (parent) and distal (child) segments and the output can be expressed in either segment frames or the ground frame. This study looked at the forces in the local frame on the tibia (child/distal segment).

Computed Muscle Control (CMC): CMC works in a similar manner to SO, but instead of estimating muscle activations it uses EMG data to compute generalized forces.

APPENDIX B: Joint Reaction Analysis Results Using Static Optimization

Table B-1: Summary of maximum average knee joint contact forces and moments obtained from joint reaction analysis for ACLR and Contralateral knees during Gait (G), Cycling Resistance 1, (C1), and Cycling Resistance 2 (C2) training (n=10)..

Maximum		G	C1	C2
AP Force	ACLR	0.807 ± 0.376	0.729 ± 0.317	1.481 ± 0.560
	Contralateral	0.809 ± 0.350	0.717 ± 0.288	1.502 ± 0.459
Comp Force	ACLR	3.909 ± 1.156	0.555 ± 0.147	0.726 ± 0.257
	Contralateral	3.846 ± 0.813	0.561 ± 0.186	0.690 ± 0.241
ML Force	ACLR	0.105 ± 0.072	0.037 ± 0.041	0.078 ± 0.059
	Contralateral	0.101 ± 0.073	0.033 ± 0.017	0.072 ± 0.027
AA Moment	ACLR	0.264 ± 0.061	0.021 ± 0.040	0.047 ± 0.067
	Contralateral	0.283 ± 0.106	0.028 ± 0.047	0.057 ± 0.086
IE Moment	ACLR	0.059 ± 0.026	-0.001 ± 0.005	0.001 ± 0.010
	Contralateral	0.082 ± 0.049	0.001 ± 0.009	0.000 ± 0.012
FE Moment	ACLR	0.051 ± 0.027	0.032 ± 0.013	0.050 ± 0.021
	Contralateral	0.060 ± 0.034	0.034 ± 0.011	0.042 ± 0.021

Table B-2: Summary of minimum average knee joint contact forces and moments obtained from joint reaction analysis for ACLR and Contralateral knees during Gait (G), Cycling Resistance 1, (C1), and Cycling Resistance 2 (C2) training (n=10)..

Minimum		G	C1	C2
AP Force	ACLR	-0.060 ± 0.059	0.105 ± 0.072	0.124 ± 0.073
	Contralateral	-0.082 ± 0.082	0.111 ± 0.043	0.129 ± 0.041
Comp Force	ACLR	0.001 ± 0.019	0.016 ± 0.117	0.037 ± 0.075
	Contralateral	0.092 ± 0.285	0.000 ± 0.076	0.016 ± 0.072
ML Force	ACLR	-0.161 ± 0.057	-0.018 ± 0.016	-0.023 ± 0.025
	Contralateral	-0.171 ± 0.035	-0.016 ± 0.015	-0.024 ± 0.020
AA Moment	ACLR	-0.056 ± 0.016	-0.036 ± 0.028	-0.062 ± 0.064
	Contralateral	-0.047 ± 0.038	-0.040 ± 0.033	-0.067 ± 0.060
IE Moment	ACLR	-0.078 ± 0.031	-0.043 ± 0.017	-0.084 ± 0.031
	Contralateral	-0.088 ± 0.034	-0.044 ± 0.013	-0.087 ± 0.025
FE Moment	ACLR	-0.019 ± 0.040	-0.002 ± 0.009	-0.003 ± 0.010
	Contralateral	-0.020 ± 0.028	-0.003 ± 0.006	-0.005 ± 0.009

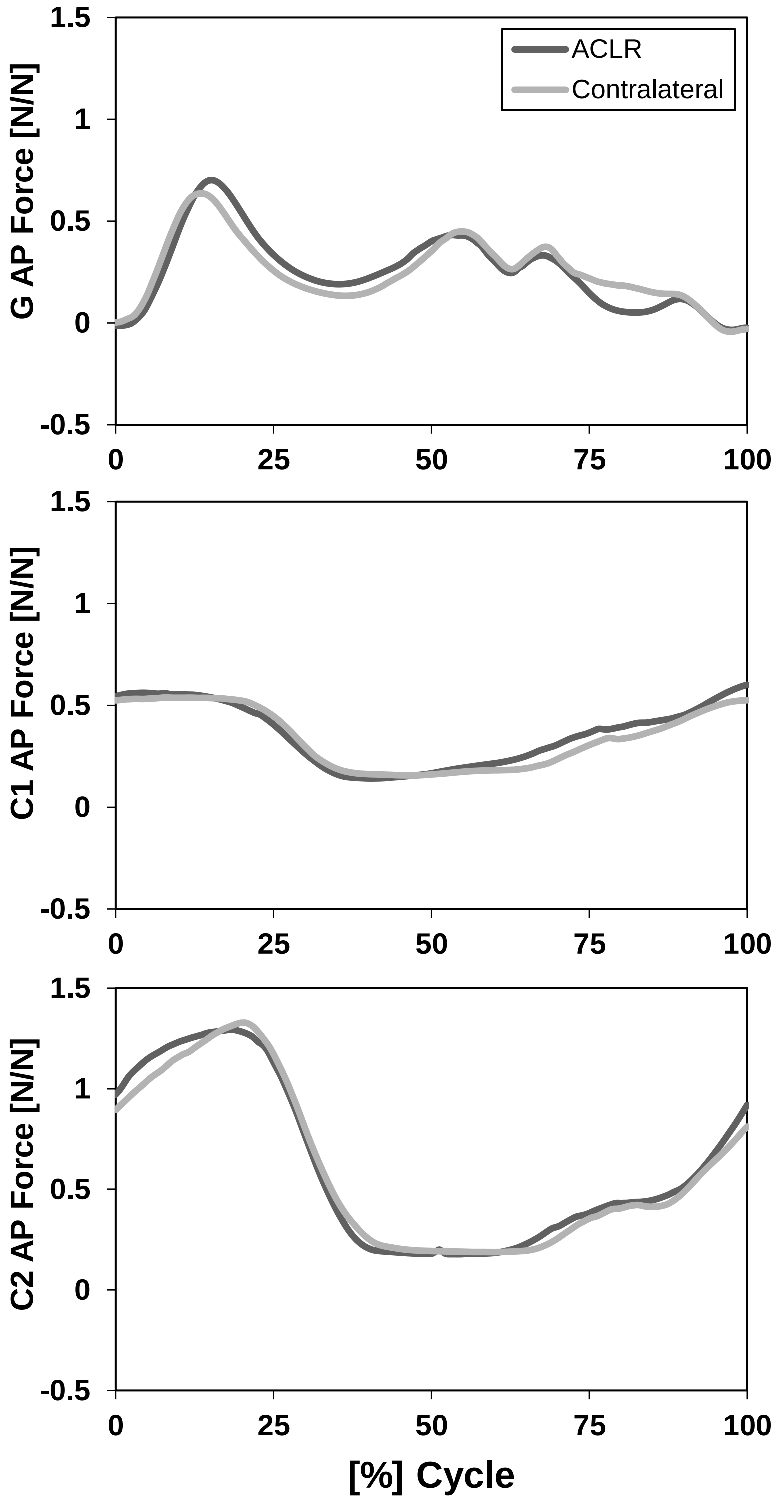

Figure B-1: Average anterior(+)-posterior(-) knee joint contact force during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=10).

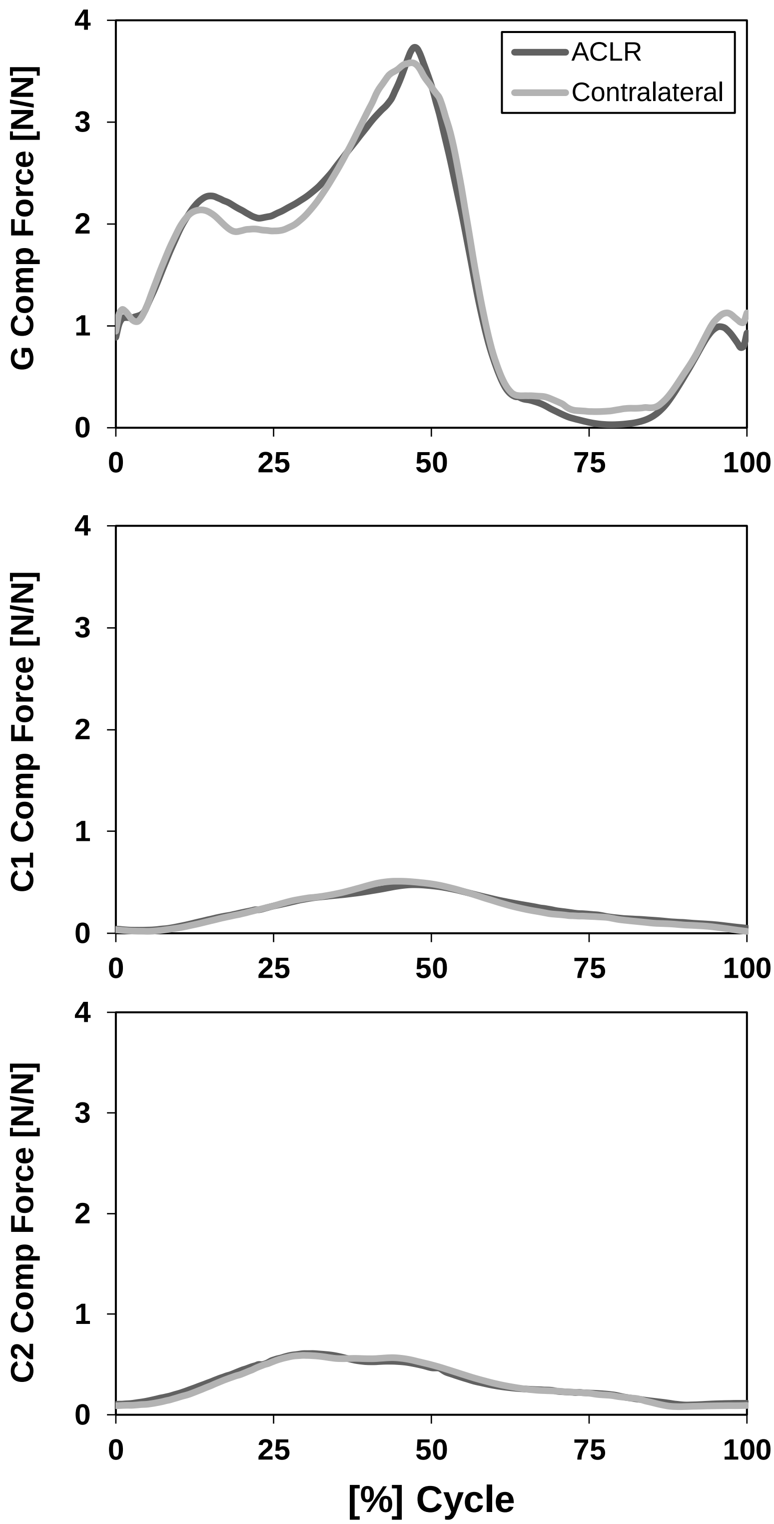

Figure B-2: Average compressive knee joint contact force during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=10).

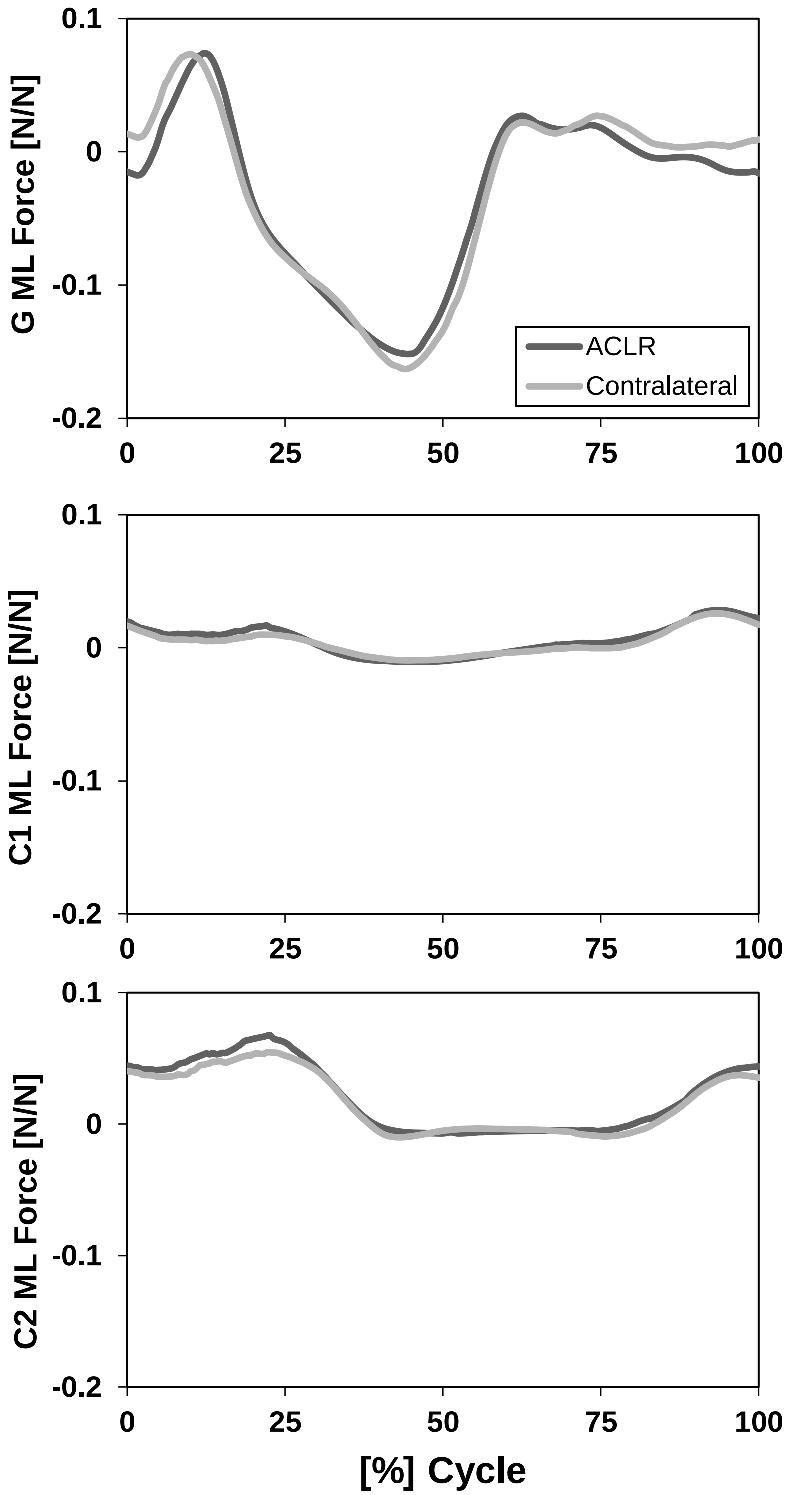

Figure B-3: Average medial(+)-lateral(-) knee joint contact force during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=10).

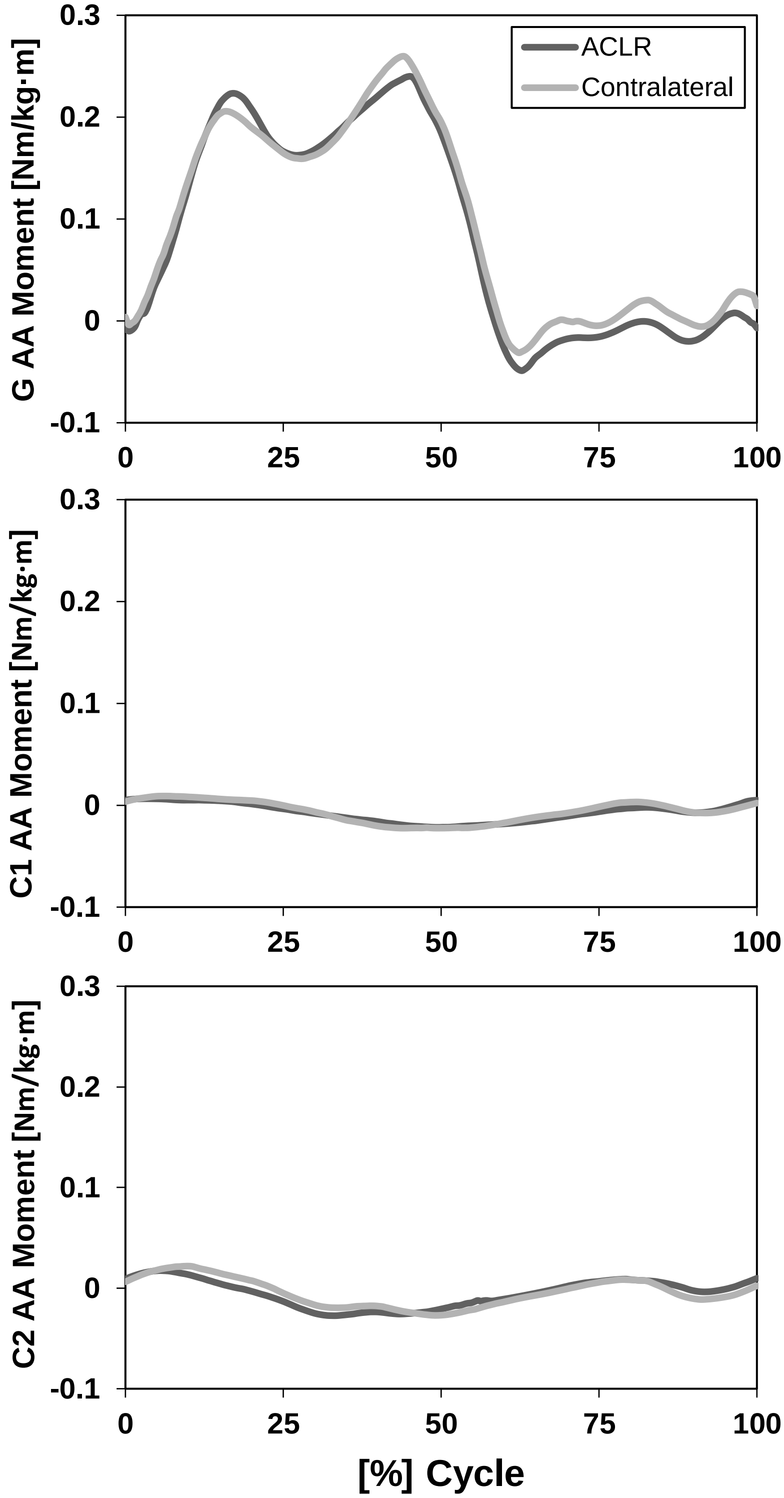

Figure B-4: Average abduction(+)-adduction(-) knee joint contact moment during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=10).

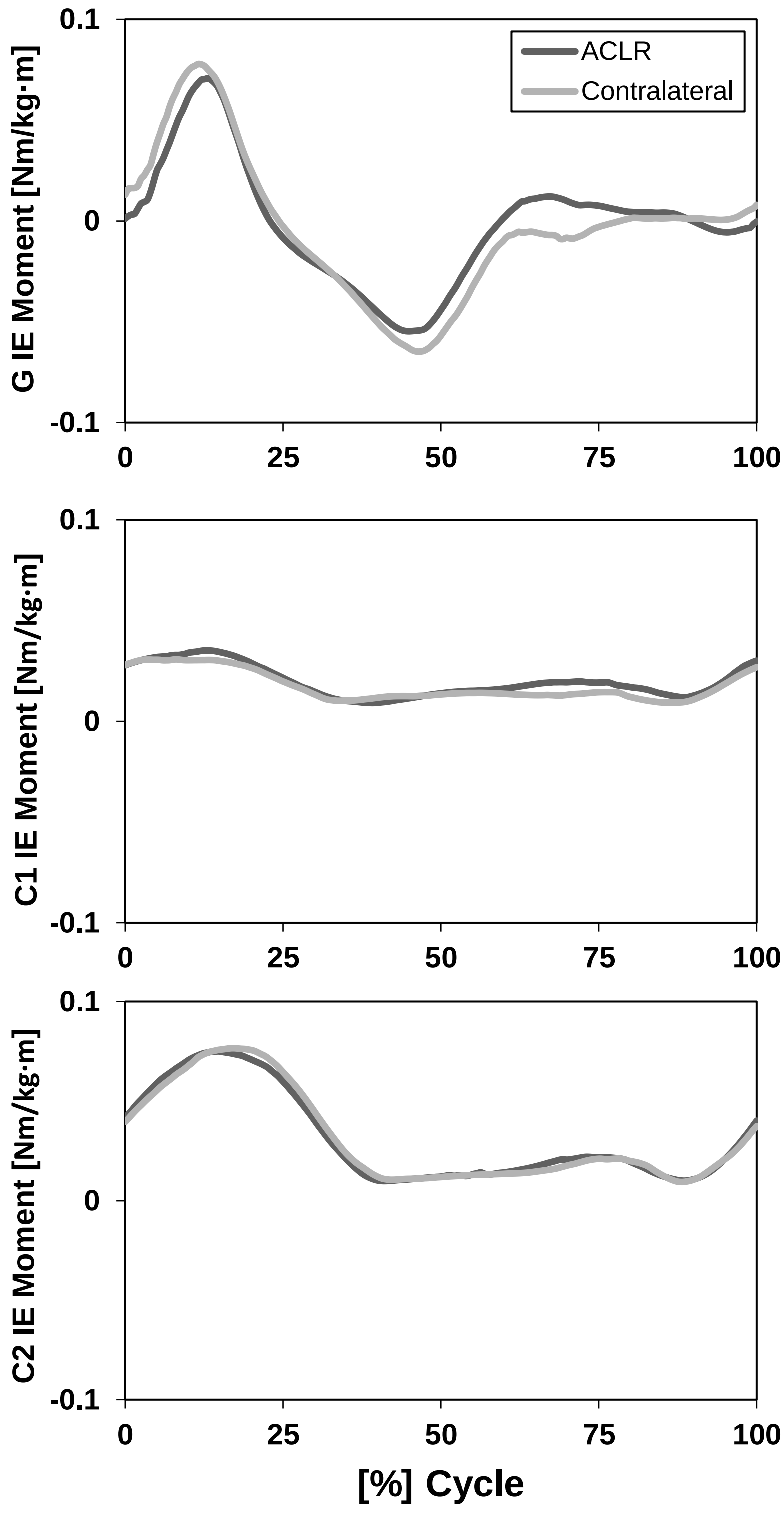

Figure B-5: Average internal(+)-external(-) rotation knee joint contact moment during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=10).

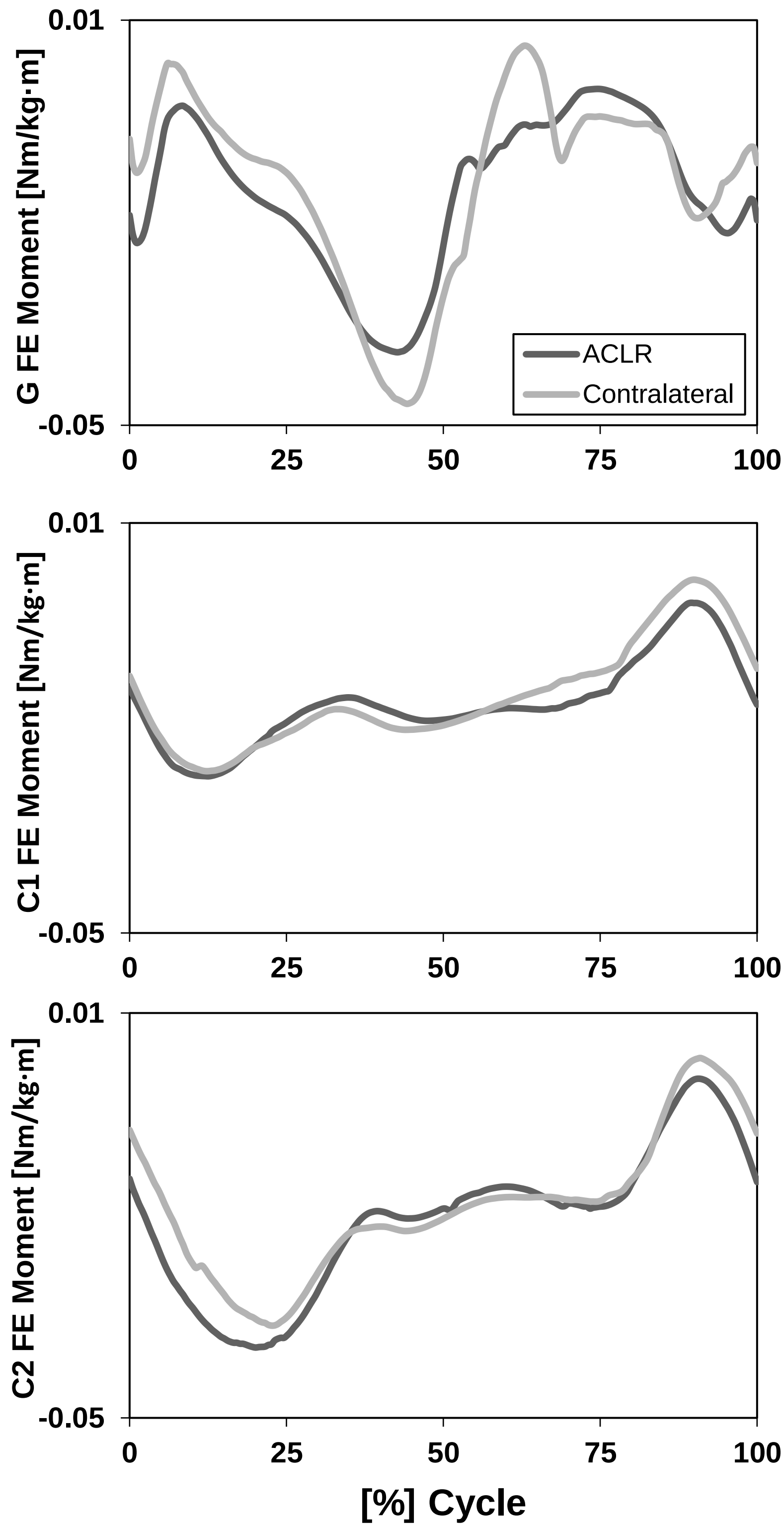

Figure B-6: Average flexion(+)-extension(-) knee joint contact moment during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=10).

APPENDIX C: Statistical Summary of Joint Reaction Results

Two Way Repeated Measures ANOVA with Post-Hoc Tukey Test

General Linear Model: Max Comp Force versus Exercise, Leg

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	140.622	70.3111	187.77	0.000
Leg	1	0.016	0.0165	0.04	0.835
Exercise*Leg	2	0.033	0.0167	0.04	0.957
Error	54	20.220	0.3745		
Total	59	160.893			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.611926	87.43%	86.27%	84.48%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.7088	0.0790	21.63	0.000	
Exercise					
Cycling1	-1.159	0.112	-10.38	0.000	1.33
Cycling2	-1.004	0.112	-8.99	0.000	1.33
Leg					
ACLR	0.0166	0.0790	0.21	0.835	1.00
Exercise*Leg					
Cycling1 ACLR	-0.028	0.112	-0.25	0.804	1.33
Cycling2 ACLR	-0.002	0.112	-0.02	0.986	1.33

Comparisons for Max Comp Force

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping	
Gait ACLR	10	3.91833	A	
Gait Contralateral	10	3.82555	A	
Cycling2 ACLR	10	0.71933		B
Cycling2 Contralateral	10	0.69025		B
Cycling1 Contralateral	10	0.56076		B
Cycling1 ACLR	10	0.53830		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.022	0.274	(-0.786, 0.831)
(Cycling2 ACLR) - (Cycling1 ACLR)	0.181	0.274	(-0.628, 0.990)
(Cycling2 Contralateral) - (Cycling1 ACLR)	0.152	0.274	(-0.657, 0.961)
(Gait ACLR) - (Cycling1 ACLR)	3.380	0.274	(2.571, 4.189)
(Gait Contralateral) - (Cycling1 ACLR)	3.287	0.274	(2.478, 4.096)
(Cycling2 ACLR) - (Cycling1 Contralateral)	0.159	0.274	(-0.650, 0.967)
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.129	0.274	(-0.679, 0.938)
(Gait ACLR) - (Cycling1 Contralateral)	3.358	0.274	(2.549, 4.166)
(Gait Contralateral) - (Cycling1 Contralateral)	3.265	0.274	(2.456, 4.074)
(Cycling2 Contralateral) - (Cycling2 ACLR)	-0.029	0.274	(-0.838, 0.780)
(Gait ACLR) - (Cycling2 ACLR)	3.199	0.274	(2.390, 4.008)
(Gait Contralateral) - (Cycling2 ACLR)	3.106	0.274	(2.297, 3.915)
(Gait ACLR) - (Cycling2 Contralateral)	3.228	0.274	(2.419, 4.037)
(Gait Contralateral) - (Cycling2 Contralateral)	3.135	0.274	(2.326, 3.944)
(Gait Contralateral) - (Gait ACLR)	-0.093	0.274	(-0.902, 0.716)

Difference of Exercise*Leg Levels	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.08	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	0.66	0.985
(Cycling2 Contralateral) - (Cycling1 ACLR)	0.56	0.993
(Gait ACLR) - (Cycling1 ACLR)	12.35	0.000
(Gait Contralateral) - (Cycling1 ACLR)	12.01	0.000
(Cycling2 ACLR) - (Cycling1 Contralateral)	0.58	0.992
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.47	0.997
(Gait ACLR) - (Cycling1 Contralateral)	12.27	0.000
(Gait Contralateral) - (Cycling1 Contralateral)	11.93	0.000
(Cycling2 Contralateral) - (Cycling2 ACLR)	-0.11	1.000
(Gait ACLR) - (Cycling2 ACLR)	11.69	0.000
(Gait Contralateral) - (Cycling2 ACLR)	11.35	0.000
(Gait ACLR) - (Cycling2 Contralateral)	11.80	0.000
(Gait Contralateral) - (Cycling2 Contralateral)	11.46	0.000
(Gait Contralateral) - (Gait ACLR)	-0.34	0.999

Individual confidence level = 99.54%

Figure C-1: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing TF compressive force between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Max AP Force versus Exercise, Leg

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	6.8724	3.43619	25.08	0.000
Leg	1	0.0101	0.01011	0.07	0.787
Exercise*Leg	2	0.0207	0.01037	0.08	0.927
Error	54	7.3974	0.13699		
Total	59	14.3006			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.370121	48.27%	43.48%	36.14%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.9905	0.0478	20.73	0.000	
Exercise					
Cycling1	-0.2847	0.0676	-4.21	0.000	1.33
Cycling2	0.4755	0.0676	7.04	0.000	1.33
Leg					
ACLR	-0.0130	0.0478	-0.27	0.787	1.00
Exercise*Leg					
Cycling1 ACLR	0.0015	0.0676	0.02	0.983	1.33
Cycling2 ACLR	-0.0235	0.0676	-0.35	0.730	1.33

Comparisons for Max AP Force

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping	
Cycling2 Contralateral	10	1.50246	A	
Cycling2 ACLR	10	1.42955	A	
Gait ACLR	10	0.80859		B
Gait Contralateral	10	0.79057		B
Cycling1 Contralateral	10	0.71728		B
Cycling1 ACLR	10	0.69429		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.023	0.166	(-0.466, 0.512)
(Cycling2 ACLR) - (Cycling1 ACLR)	0.735	0.166	(0.246, 1.224)
(Cycling2 Contralateral) - (Cycling1 ACLR)	0.808	0.166	(0.319, 1.297)
(Gait ACLR) - (Cycling1 ACLR)	0.114	0.166	(-0.375, 0.604)
(Gait Contralateral) - (Cycling1 ACLR)	0.096	0.166	(-0.393, 0.586)
(Cycling2 ACLR) - (Cycling1 Contralateral)	0.712	0.166	(0.223, 1.202)
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.785	0.166	(0.296, 1.274)
(Gait ACLR) - (Cycling1 Contralateral)	0.091	0.166	(-0.398, 0.581)
(Gait Contralateral) - (Cycling1 Contralateral)	0.073	0.166	(-0.416, 0.563)
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.073	0.166	(-0.416, 0.562)
(Gait ACLR) - (Cycling2 ACLR)	-0.621	0.166	(-1.110, -0.132)
(Gait Contralateral) - (Cycling2 ACLR)	-0.639	0.166	(-1.128, -0.150)
(Gait ACLR) - (Cycling2 Contralateral)	-0.694	0.166	(-1.183, -0.205)
(Gait Contralateral) - (Cycling2 Contralateral)	-0.712	0.166	(-1.201, -0.223)
(Gait Contralateral) - (Gait ACLR)	-0.018	0.166	(-0.507, 0.471)

Difference of Exercise*Leg Levels	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.14	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	4.44	0.001
(Cycling2 Contralateral) - (Cycling1 ACLR)	4.88	0.000
(Gait ACLR) - (Cycling1 ACLR)	0.69	0.982
(Gait Contralateral) - (Cycling1 ACLR)	0.58	0.992
(Cycling2 ACLR) - (Cycling1 Contralateral)	4.30	0.001
(Cycling2 Contralateral) - (Cycling1 Contralateral)	4.74	0.000
(Gait ACLR) - (Cycling1 Contralateral)	0.55	0.994
(Gait Contralateral) - (Cycling1 Contralateral)	0.44	0.998
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.44	0.998
(Gait ACLR) - (Cycling2 ACLR)	-3.75	0.005
(Gait Contralateral) - (Cycling2 ACLR)	-3.86	0.004
(Gait ACLR) - (Cycling2 Contralateral)	-4.19	0.001
(Gait Contralateral) - (Cycling2 Contralateral)	-4.30	0.001
(Gait Contralateral) - (Gait ACLR)	-0.11	1.000

Individual confidence level = 99.54%

Figure C-2: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing maximum AP shear force between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Min AP Force versus Exercise, Leg

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	0.479839	0.239920	71.58	0.000
Leg	1	0.000297	0.000297	0.09	0.767
Exercise*Leg	2	0.005359	0.002679	0.80	0.455
Error	54	0.181007	0.003352		
Total	59	0.666502			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0578963	72.84%	70.33%	66.47%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.05249	0.00747	7.02	0.000	
Exercise					
Cycling1	0.0545	0.0106	5.15	0.000	1.33
Cycling2	0.0716	0.0106	6.77	0.000	1.33
Leg					
ACLR	0.00223	0.00747	0.30	0.767	1.00
Exercise*Leg					
Cycling1 ACLR	-0.0061	0.0106	-0.58	0.566	1.33
Cycling2 ACLR	-0.0073	0.0106	-0.69	0.496	1.33

Comparisons for Min AP Force

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping	
Cycling2 Contralateral	10	0.129120	A	
Cycling2 ACLR	10	0.119072	A	
Cycling1 Contralateral	10	0.110830	A	
Cycling1 ACLR	10	0.103087	A	
Gait ACLR	10	-0.058022		B
Gait Contralateral	10	-0.089171		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.0077	0.0259	(-0.0688, 0.0843)	0.30	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	0.0160	0.0259	(-0.0605, 0.0925)	0.62	0.989
(Cycling2 Contralateral) - (Cycling1 ACLR)	0.0260	0.0259	(-0.0505, 0.1026)	1.01	0.914
(Gait ACLR) - (Cycling1 ACLR)	-0.1611	0.0259	(-0.2376, -0.0846)	-6.22	0.000
(Gait Contralateral) - (Cycling1 ACLR)	-0.1923	0.0259	(-0.2688, -0.1157)	-7.43	0.000
(Cycling2 ACLR) - (Cycling1 Contralateral)	0.0082	0.0259	(-0.0683, 0.0848)	0.32	1.000
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.0183	0.0259	(-0.0582, 0.0948)	0.71	0.980
(Gait ACLR) - (Cycling1 Contralateral)	-0.1689	0.0259	(-0.2454, -0.0923)	-6.52	0.000
(Gait Contralateral) - (Cycling1 Contralateral)	-0.2000	0.0259	(-0.2765, -0.1235)	-7.72	0.000
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.0100	0.0259	(-0.0665, 0.0866)	0.39	0.999
(Gait ACLR) - (Cycling2 ACLR)	-0.1771	0.0259	(-0.2536, -0.1006)	-6.84	0.000
(Gait Contralateral) - (Cycling2 ACLR)	-0.2082	0.0259	(-0.2848, -0.1317)	-8.04	0.000
(Gait ACLR) - (Cycling2 Contralateral)	-0.1871	0.0259	(-0.2637, -0.1106)	-7.23	0.000
(Gait Contralateral) - (Cycling2 Contralateral)	-0.2183	0.0259	(-0.2948, -0.1418)	-8.43	0.000
(Gait Contralateral) - (Gait ACLR)	-0.0311	0.0259	(-0.1077, 0.0454)	-1.20	0.833

Individual confidence level = 99.54%

Figure C-3: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing minimum AP shear force between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Max ML Force versus Exercise, Leg

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	0.041083	0.020542	10.05	0.000
Leg	1	0.000698	0.000698	0.34	0.561
Exercise*Leg	2	0.000903	0.000451	0.22	0.803
Error	54	0.110424	0.002045		
Total	59	0.153108			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0452205	27.88%	21.20%	10.96%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.06731	0.00584	11.53	0.000	
Exercise					
Cycling1	-0.03486	0.00826	-4.22	0.000	1.33
Cycling2	0.00669	0.00826	0.81	0.422	1.33
Leg					
ACLR	0.00341	0.00584	0.58	0.561	1.00
Exercise*Leg					
Cycling1 ACLR	-0.00380	0.00826	-0.46	0.648	1.33
Cycling2 ACLR	-0.00153	0.00826	-0.19	0.854	1.33

Comparisons for Max ML Force

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping	
Gait ACLR	10	0.104228	A	
Gait Contralateral	10	0.086752	A	B
Cycling2 ACLR	10	0.075877	A	B
Cycling2 Contralateral	10	0.072116	A	B
Cycling1 Contralateral	10	0.032833		B
Cycling1 ACLR	10	0.032064		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.0008	0.0202	(-0.0590, 0.0605)
(Cycling2 ACLR) - (Cycling1 ACLR)	0.0438	0.0202	(-0.0160, 0.1036)
(Cycling2 Contralateral) - (Cycling1 ACLR)	0.0401	0.0202	(-0.0197, 0.0998)
(Gait ACLR) - (Cycling1 ACLR)	0.0722	0.0202	(0.0124, 0.1319)
(Gait Contralateral) - (Cycling1 ACLR)	0.0547	0.0202	(-0.0051, 0.1145)
(Cycling2 ACLR) - (Cycling1 Contralateral)	0.0430	0.0202	(-0.0167, 0.1028)
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.0393	0.0202	(-0.0205, 0.0991)
(Gait ACLR) - (Cycling1 Contralateral)	0.0714	0.0202	(0.0116, 0.1312)
(Gait Contralateral) - (Cycling1 Contralateral)	0.0539	0.0202	(-0.0059, 0.1137)
(Cycling2 Contralateral) - (Cycling2 ACLR)	-0.0038	0.0202	(-0.0635, 0.0560)
(Gait ACLR) - (Cycling2 ACLR)	0.0284	0.0202	(-0.0314, 0.0881)
(Gait Contralateral) - (Cycling2 ACLR)	0.0109	0.0202	(-0.0489, 0.0706)
(Gait ACLR) - (Cycling2 Contralateral)	0.0321	0.0202	(-0.0277, 0.0919)
(Gait Contralateral) - (Cycling2 Contralateral)	0.0146	0.0202	(-0.0451, 0.0744)
(Gait Contralateral) - (Gait ACLR)	-0.0175	0.0202	(-0.0773, 0.0423)

Difference of Exercise*Leg Levels	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.04	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	2.17	0.270
(Cycling2 Contralateral) - (Cycling1 ACLR)	1.98	0.367
(Gait ACLR) - (Cycling1 ACLR)	3.57	0.009
(Gait Contralateral) - (Cycling1 ACLR)	2.70	0.091
(Cycling2 ACLR) - (Cycling1 Contralateral)	2.13	0.289
(Cycling2 Contralateral) - (Cycling1 Contralateral)	1.94	0.388
(Gait ACLR) - (Cycling1 Contralateral)	3.53	0.011
(Gait Contralateral) - (Cycling1 Contralateral)	2.67	0.099
(Cycling2 Contralateral) - (Cycling2 ACLR)	-0.19	1.000
(Gait ACLR) - (Cycling2 ACLR)	1.40	0.726
(Gait Contralateral) - (Cycling2 ACLR)	0.54	0.994
(Gait ACLR) - (Cycling2 Contralateral)	1.59	0.610
(Gait Contralateral) - (Cycling2 Contralateral)	0.72	0.978
(Gait Contralateral) - (Gait ACLR)	-0.86	0.953

Individual confidence level = 99.54%

Figure C-4: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing maximum ML shear force between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Min ML Force versus Exercise, Leg

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	0.289944	0.144972	151.22	0.000
Leg	1	0.000170	0.000170	0.18	0.675
Exercise*Leg	2	0.000505	0.000252	0.26	0.769
Error	54	0.051768	0.000959		
Total	59	0.342387			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0309622	84.88%	83.48%	81.33%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.06937	0.00400	-17.36	0.000	
Exercise					
Cycling1	0.05242	0.00565	9.27	0.000	1.33
Cycling2	0.04582	0.00565	8.11	0.000	1.33
Leg					
ACLR	0.00169	0.00400	0.42	0.675	1.00
Exercise*Leg					
Cycling1 ACLR	-0.00274	0.00565	-0.49	0.629	1.33
Cycling2 ACLR	-0.00127	0.00565	-0.22	0.823	1.33

Comparisons for Min ML Force

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping	
Cycling1 Contralateral	10	-0.015895	A	
Cycling1 ACLR	10	-0.018012	A	
Cycling2 ACLR	10	-0.023139	A	
Cycling2 Contralateral	10	-0.023971	A	
Gait ACLR	10	-0.161910		B
Gait Contralateral	10	-0.173306		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.0021	0.0138	(-0.0388, 0.0430)
(Cycling2 ACLR) - (Cycling1 ACLR)	-0.0051	0.0138	(-0.0461, 0.0358)
(Cycling2 Contralateral) - (Cycling1 ACLR)	-0.0060	0.0138	(-0.0469, 0.0350)
(Gait ACLR) - (Cycling1 ACLR)	-0.1439	0.0138	(-0.1848, -0.1030)
(Gait Contralateral) - (Cycling1 ACLR)	-0.1553	0.0138	(-0.1962, -0.1144)
(Cycling2 ACLR) - (Cycling1 Contralateral)	-0.0072	0.0138	(-0.0482, 0.0337)
(Cycling2 Contralateral) - (Cycling1 Contralateral)	-0.0081	0.0138	(-0.0490, 0.0329)
(Gait ACLR) - (Cycling1 Contralateral)	-0.1460	0.0138	(-0.1869, -0.1051)
(Gait Contralateral) - (Cycling1 Contralateral)	-0.1574	0.0138	(-0.1983, -0.1165)
(Cycling2 Contralateral) - (Cycling2 ACLR)	-0.0008	0.0138	(-0.0418, 0.0401)
(Gait ACLR) - (Cycling2 ACLR)	-0.1388	0.0138	(-0.1797, -0.0978)
(Gait Contralateral) - (Cycling2 ACLR)	-0.1502	0.0138	(-0.1911, -0.1092)
(Gait ACLR) - (Cycling2 Contralateral)	-0.1379	0.0138	(-0.1789, -0.0970)
(Gait Contralateral) - (Cycling2 Contralateral)	-0.1493	0.0138	(-0.1903, -0.1084)
(Gait Contralateral) - (Gait ACLR)	-0.0114	0.0138	(-0.0523, 0.0295)

Difference of Exercise*Leg Levels	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.15	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	-0.37	0.999
(Cycling2 Contralateral) - (Cycling1 ACLR)	-0.43	0.998
(Gait ACLR) - (Cycling1 ACLR)	-10.39	0.000
(Gait Contralateral) - (Cycling1 ACLR)	-11.22	0.000
(Cycling2 ACLR) - (Cycling1 Contralateral)	-0.52	0.995
(Cycling2 Contralateral) - (Cycling1 Contralateral)	-0.58	0.992
(Gait ACLR) - (Cycling1 Contralateral)	-10.55	0.000
(Gait Contralateral) - (Cycling1 Contralateral)	-11.37	0.000
(Cycling2 Contralateral) - (Cycling2 ACLR)	-0.06	1.000
(Gait ACLR) - (Cycling2 ACLR)	-10.02	0.000
(Gait Contralateral) - (Cycling2 ACLR)	-10.84	0.000
(Gait ACLR) - (Cycling2 Contralateral)	-9.96	0.000
(Gait Contralateral) - (Cycling2 Contralateral)	-10.78	0.000
(Gait Contralateral) - (Gait ACLR)	-0.82	0.962

Individual confidence level = 99.54%

Figure C-5: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing minimum ML shear force between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Max AA Moment versus Exercise, Leg

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	0.74543	0.372715	71.48	0.000
Leg	1	0.00117	0.001167	0.22	0.638
Exercise*Leg	2	0.00006	0.000030	0.01	0.994
Error	54	0.28156	0.005214		
Total	59	1.02822			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0722087	72.62%	70.08%	66.19%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.11761	0.00932	12.62	0.000	
Exercise					
Cycling1	-0.0929	0.0132	-7.04	0.000	1.33
Cycling2	-0.0639	0.0132	-4.85	0.000	1.33
Leg					
ACLR	-0.00441	0.00932	-0.47	0.638	1.00
Exercise*Leg					
Cycling1 ACLR	0.0007	0.0132	0.05	0.957	1.33
Cycling2 ACLR	0.0007	0.0132	0.05	0.957	1.33

Comparisons for Max AA Moment

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping	
Gait Contralateral	10	0.280172	A	
Gait ACLR	10	0.268521	A	
Cycling2 Contralateral	10	0.057431		B
Cycling2 ACLR	10	0.050024		B
Cycling1 Contralateral	10	0.028446		B
Cycling1 ACLR	10	0.021042		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.0074	0.0323	(-0.0880, 0.1029)	0.23	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	0.0290	0.0323	(-0.0665, 0.1244)	0.90	0.945
(Cycling2 Contralateral) - (Cycling1 ACLR)	0.0364	0.0323	(-0.0591, 0.1318)	1.13	0.868
(Gait ACLR) - (Cycling1 ACLR)	0.2475	0.0323	(0.1520, 0.3429)	7.66	0.000
(Gait Contralateral) - (Cycling1 ACLR)	0.2591	0.0323	(0.1637, 0.3546)	8.02	0.000
(Cycling2 ACLR) - (Cycling1 Contralateral)	0.0216	0.0323	(-0.0739, 0.1170)	0.67	0.985
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.0290	0.0323	(-0.0665, 0.1244)	0.90	0.945
(Gait ACLR) - (Cycling1 Contralateral)	0.2401	0.0323	(0.1446, 0.3355)	7.43	0.000
(Gait Contralateral) - (Cycling1 Contralateral)	0.2517	0.0323	(0.1563, 0.3472)	7.80	0.000
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.0074	0.0323	(-0.0880, 0.1029)	0.23	1.000
(Gait ACLR) - (Cycling2 ACLR)	0.2185	0.0323	(0.1230, 0.3139)	6.77	0.000
(Gait Contralateral) - (Cycling2 ACLR)	0.2301	0.0323	(0.1347, 0.3256)	7.13	0.000
(Gait ACLR) - (Cycling2 Contralateral)	0.2111	0.0323	(0.1156, 0.3065)	6.54	0.000
(Gait Contralateral) - (Cycling2 Contralateral)	0.2227	0.0323	(0.1273, 0.3182)	6.90	0.000
(Gait Contralateral) - (Gait ACLR)	0.0117	0.0323	(-0.0838, 0.1071)	0.36	0.999

Individual confidence level = 99.54%

Figure C-6: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing maximum AA moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Min AA Moment versus Exercise, Leg

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	0.006682	0.003341	1.89	0.161
Leg	1	0.000120	0.000120	0.07	0.796
Exercise*Leg	2	0.000057	0.000029	0.02	0.984
Error	54	0.095490	0.001768		
Total	59	0.102348			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0420515	6.70%	0.00%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.05341	0.00543	-9.84	0.000	
Exercise					
Cycling1	0.01424	0.00768	1.85	0.069	1.33
Cycling2	-0.01099	0.00768	-1.43	0.158	1.33
Leg					
ACLR	0.00141	0.00543	0.26	0.796	1.00
Exercise*Leg					
Cycling1 ACLR	-0.00027	0.00768	-0.03	0.973	1.33
Cycling2 ACLR	0.00131	0.00768	0.17	0.865	1.33

Comparisons for Min AA Moment

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping
Cycling1 ACLR	10	-0.0380233	A
Cycling1 Contralateral	10	-0.0403157	A
Gait ACLR	10	-0.0562809	A
Gait Contralateral	10	-0.0570155	A
Cycling2 ACLR	10	-0.0616809	A
Cycling2 Contralateral	10	-0.0671217	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI
(Cycling1 Contralateral) - (Cycling1 ACLR)	-0.0023	0.0188	(-0.0579, 0.0533)
(Cycling2 ACLR) - (Cycling1 ACLR)	-0.0237	0.0188	(-0.0792, 0.0319)
(Cycling2 Contralateral) - (Cycling1 ACLR)	-0.0291	0.0188	(-0.0847, 0.0265)
(Gait ACLR) - (Cycling1 ACLR)	-0.0183	0.0188	(-0.0738, 0.0373)
(Gait Contralateral) - (Cycling1 ACLR)	-0.0190	0.0188	(-0.0746, 0.0366)
(Cycling2 ACLR) - (Cycling1 Contralateral)	-0.0214	0.0188	(-0.0770, 0.0342)
(Cycling2 Contralateral) - (Cycling1 Contralateral)	-0.0268	0.0188	(-0.0824, 0.0288)
(Gait ACLR) - (Cycling1 Contralateral)	-0.0160	0.0188	(-0.0716, 0.0396)
(Gait Contralateral) - (Cycling1 Contralateral)	-0.0167	0.0188	(-0.0723, 0.0389)
(Cycling2 Contralateral) - (Cycling2 ACLR)	-0.0054	0.0188	(-0.0610, 0.0501)
(Gait ACLR) - (Cycling2 ACLR)	0.0054	0.0188	(-0.0502, 0.0610)
(Gait Contralateral) - (Cycling2 ACLR)	0.0047	0.0188	(-0.0509, 0.0603)
(Gait ACLR) - (Cycling2 Contralateral)	0.0108	0.0188	(-0.0447, 0.0664)
(Gait Contralateral) - (Cycling2 Contralateral)	0.0101	0.0188	(-0.0455, 0.0657)
(Gait Contralateral) - (Gait ACLR)	-0.0007	0.0188	(-0.0563, 0.0549)

Difference of Exercise*Leg Levels	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	-0.12	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	-1.26	0.806
(Cycling2 Contralateral) - (Cycling1 ACLR)	-1.55	0.636
(Gait ACLR) - (Cycling1 ACLR)	-0.97	0.925
(Gait Contralateral) - (Cycling1 ACLR)	-1.01	0.913
(Cycling2 ACLR) - (Cycling1 Contralateral)	-1.14	0.864
(Cycling2 Contralateral) - (Cycling1 Contralateral)	-1.43	0.712
(Gait ACLR) - (Cycling1 Contralateral)	-0.85	0.957
(Gait Contralateral) - (Cycling1 Contralateral)	-0.89	0.948
(Cycling2 Contralateral) - (Cycling2 ACLR)	-0.29	1.000
(Gait ACLR) - (Cycling2 ACLR)	0.29	1.000
(Gait Contralateral) - (Cycling2 ACLR)	0.25	1.000
(Gait ACLR) - (Cycling2 Contralateral)	0.58	0.992
(Gait Contralateral) - (Cycling2 Contralateral)	0.54	0.994
(Gait Contralateral) - (Gait ACLR)	-0.04	1.000

Individual confidence level = 99.54%

Figure C-7: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing minimum AA moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Max IntExt Moment versus Exercise, Leg

Method

Factor coding	(-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	0.019867	0.009933	17.63	0.000
Leg	1	0.000417	0.000417	0.74	0.394
Exercise*Leg	2	0.000075	0.000037	0.07	0.936
Error	54	0.030427	0.000563		
Total	59	0.050785			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0237375	40.09%	34.54%	26.03%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.06902	0.00306	22.52	0.000	
Exercise					
Cycling1	-0.02570	0.00433	-5.93	0.000	1.33
Cycling2	0.01397	0.00433	3.22	0.002	1.33
Leg					
ACLR	-0.00263	0.00306	-0.86	0.394	1.00
Exercise*Leg					
Cycling1 ACLR	0.00157	0.00433	0.36	0.719	1.33
Cycling2 ACLR	-0.00091	0.00433	-0.21	0.835	1.33

Comparisons for Max IntExt Moment

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping	
Cycling2 Contralateral	10	0.0865368	A	
Gait Contralateral	10	0.0840534	A	
Cycling2 ACLR	10	0.0794507	A	
Gait ACLR	10	0.0774594	A	
Cycling1 Contralateral	10	0.0443882		B
Cycling1 ACLR	10	0.0422585		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.0021	0.0106	(-0.0292, 0.0335)
(Cycling2 ACLR) - (Cycling1 ACLR)	0.0372	0.0106	(0.0058, 0.0686)
(Cycling2 Contralateral) - (Cycling1 ACLR)	0.0443	0.0106	(0.0129, 0.0757)
(Gait ACLR) - (Cycling1 ACLR)	0.0352	0.0106	(0.0038, 0.0666)
(Gait Contralateral) - (Cycling1 ACLR)	0.0418	0.0106	(0.0104, 0.0732)
(Cycling2 ACLR) - (Cycling1 Contralateral)	0.0351	0.0106	(0.0037, 0.0664)
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.0421	0.0106	(0.0108, 0.0735)
(Gait ACLR) - (Cycling1 Contralateral)	0.0331	0.0106	(0.0017, 0.0644)
(Gait Contralateral) - (Cycling1 Contralateral)	0.0397	0.0106	(0.0083, 0.0710)
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.0071	0.0106	(-0.0243, 0.0385)
(Gait ACLR) - (Cycling2 ACLR)	-0.0020	0.0106	(-0.0334, 0.0294)
(Gait Contralateral) - (Cycling2 ACLR)	0.0046	0.0106	(-0.0268, 0.0360)
(Gait ACLR) - (Cycling2 Contralateral)	-0.0091	0.0106	(-0.0405, 0.0223)
(Gait Contralateral) - (Cycling2 Contralateral)	-0.0025	0.0106	(-0.0339, 0.0289)
(Gait Contralateral) - (Gait ACLR)	0.0066	0.0106	(-0.0248, 0.0380)

Difference of Exercise*Leg Levels	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.20	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	3.50	0.011
(Cycling2 Contralateral) - (Cycling1 ACLR)	4.17	0.001
(Gait ACLR) - (Cycling1 ACLR)	3.32	0.019
(Gait Contralateral) - (Cycling1 ACLR)	3.94	0.003
(Cycling2 ACLR) - (Cycling1 Contralateral)	3.30	0.020
(Cycling2 Contralateral) - (Cycling1 Contralateral)	3.97	0.003
(Gait ACLR) - (Cycling1 Contralateral)	3.12	0.033
(Gait Contralateral) - (Cycling1 Contralateral)	3.74	0.006
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.67	0.985
(Gait ACLR) - (Cycling2 ACLR)	-0.19	1.000
(Gait Contralateral) - (Cycling2 ACLR)	0.43	0.998
(Gait ACLR) - (Cycling2 Contralateral)	-0.86	0.955
(Gait Contralateral) - (Cycling2 Contralateral)	-0.23	1.000
(Gait Contralateral) - (Gait ACLR)	0.62	0.989

Individual confidence level = 99.54%

Figure C-8: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing maximum IE moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Min IntExt Moment versus Exercise, Leg

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	0.054968	0.027484	74.46	0.000
Leg	1	0.000167	0.000167	0.45	0.504
Exercise*Leg	2	0.000273	0.000136	0.37	0.693
Error	54	0.019932	0.000369		
Total	59	0.075339			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0192121	73.54%	71.09%	67.34%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.02157	0.00248	-8.70	0.000	
Exercise					
Cycling1	0.02162	0.00351	6.16	0.000	1.33
Cycling2	0.02119	0.00351	6.04	0.000	1.33
Leg					
ACLR	0.00167	0.00248	0.67	0.504	1.00
Exercise*Leg					
Cycling1 ACLR	-0.00088	0.00351	-0.25	0.802	1.33
Cycling2 ACLR	-0.00205	0.00351	-0.59	0.561	1.33

Comparisons for Min IntExt Moment

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping	
Cycling1 ACLR	10	0.0008277	A	
Cycling2 Contralateral	10	0.0000045	A	
Cycling1 Contralateral	10	-0.0007375	A	
Cycling2 ACLR	10	-0.0007704	A	
Gait ACLR	10	-0.0597695		B
Gait Contralateral	10	-0.0689814		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI
(Cycling1 Contralateral) - (Cycling1 ACLR)	-0.00157	0.00859	(-0.02696, 0.02383)
(Cycling2 ACLR) - (Cycling1 ACLR)	-0.00160	0.00859	(-0.02699, 0.02380)
(Cycling2 Contralateral) - (Cycling1 ACLR)	-0.00082	0.00859	(-0.02622, 0.02457)
(Gait ACLR) - (Cycling1 ACLR)	-0.06060	0.00859	(-0.08599, -0.03520)
(Gait Contralateral) - (Cycling1 ACLR)	-0.06981	0.00859	(-0.09520, -0.04441)
(Cycling2 ACLR) - (Cycling1 Contralateral)	-0.00003	0.00859	(-0.02543, 0.02536)
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.00074	0.00859	(-0.02465, 0.02614)
(Gait ACLR) - (Cycling1 Contralateral)	-0.05903	0.00859	(-0.08443, -0.03364)
(Gait Contralateral) - (Cycling1 Contralateral)	-0.06824	0.00859	(-0.09364, -0.04285)
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.00077	0.00859	(-0.02462, 0.02617)
(Gait ACLR) - (Cycling2 ACLR)	-0.05900	0.00859	(-0.08439, -0.03360)
(Gait Contralateral) - (Cycling2 ACLR)	-0.06821	0.00859	(-0.09361, -0.04282)
(Gait ACLR) - (Cycling2 Contralateral)	-0.05977	0.00859	(-0.08517, -0.03438)
(Gait Contralateral) - (Cycling2 Contralateral)	-0.06899	0.00859	(-0.09438, -0.04359)
(Gait Contralateral) - (Gait ACLR)	-0.00921	0.00859	(-0.03461, 0.01618)

Difference of Exercise*Leg Levels	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	-0.18	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	-0.19	1.000
(Cycling2 Contralateral) - (Cycling1 ACLR)	-0.10	1.000
(Gait ACLR) - (Cycling1 ACLR)	-7.05	0.000
(Gait Contralateral) - (Cycling1 ACLR)	-8.12	0.000
(Cycling2 ACLR) - (Cycling1 Contralateral)	-0.00	1.000
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.09	1.000
(Gait ACLR) - (Cycling1 Contralateral)	-6.87	0.000
(Gait Contralateral) - (Cycling1 Contralateral)	-7.94	0.000
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.09	1.000
(Gait ACLR) - (Cycling2 ACLR)	-6.87	0.000
(Gait Contralateral) - (Cycling2 ACLR)	-7.94	0.000
(Gait ACLR) - (Cycling2 Contralateral)	-6.96	0.000
(Gait Contralateral) - (Cycling2 Contralateral)	-8.03	0.000
(Gait Contralateral) - (Gait ACLR)	-1.07	0.890

Individual confidence level = 99.54%

Figure C-9: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing minimum IE moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Max FE Moment versus Exercise, Leg

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	0.000933	0.000466	2.94	0.061
Leg	1	0.000000	0.000000	0.00	0.994
Exercise*Leg	2	0.000116	0.000058	0.37	0.695
Error	54	0.008571	0.000159		
Total	59	0.009621			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0125987	10.91%	2.66%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.00618	0.00163	3.80	0.000	
Exercise					
Cycling1	-0.00343	0.00230	-1.49	0.142	1.33
Cycling2	-0.00209	0.00230	-0.91	0.367	1.33
Leg					
ACLR	0.00001	0.00163	0.01	0.994	1.00
Exercise*Leg					
Cycling1 ACLR	-0.00073	0.00230	-0.32	0.753	1.33
Cycling2 ACLR	-0.00122	0.00230	-0.53	0.598	1.33

Comparisons for Max FE Moment

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping
Gait ACLR	10	0.0136645	A
Gait Contralateral	10	0.0097396	A
Cycling2 Contralateral	10	0.0052937	A
Cycling1 Contralateral	10	0.0034646	A
Cycling2 ACLR	10	0.0028770	A
Cycling1 ACLR	10	0.0020359	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.00143	0.00563	(-0.01522, 0.01808)
(Cycling2 ACLR) - (Cycling1 ACLR)	0.00084	0.00563	(-0.01581, 0.01749)
(Cycling2 Contralateral) - (Cycling1 ACLR)	0.00326	0.00563	(-0.01340, 0.01991)
(Gait ACLR) - (Cycling1 ACLR)	0.01163	0.00563	(-0.00502, 0.02828)
(Gait Contralateral) - (Cycling1 ACLR)	0.00770	0.00563	(-0.00895, 0.02436)
(Cycling2 ACLR) - (Cycling1 Contralateral)	-0.00059	0.00563	(-0.01724, 0.01607)
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.00183	0.00563	(-0.01482, 0.01848)
(Gait ACLR) - (Cycling1 Contralateral)	0.01020	0.00563	(-0.00645, 0.02685)
(Gait Contralateral) - (Cycling1 Contralateral)	0.00627	0.00563	(-0.01038, 0.02293)
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.00242	0.00563	(-0.01424, 0.01907)
(Gait ACLR) - (Cycling2 ACLR)	0.01079	0.00563	(-0.00587, 0.02744)
(Gait Contralateral) - (Cycling2 ACLR)	0.00686	0.00563	(-0.00979, 0.02352)
(Gait ACLR) - (Cycling2 Contralateral)	0.00837	0.00563	(-0.00828, 0.02502)
(Gait Contralateral) - (Cycling2 Contralateral)	0.00445	0.00563	(-0.01221, 0.02110)
(Gait Contralateral) - (Gait ACLR)	-0.00392	0.00563	(-0.02058, 0.01273)

Difference of Exercise*Leg Levels	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	0.25	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	0.15	1.000
(Cycling2 Contralateral) - (Cycling1 ACLR)	0.58	0.992
(Gait ACLR) - (Cycling1 ACLR)	2.06	0.321
(Gait Contralateral) - (Cycling1 ACLR)	1.37	0.746
(Cycling2 ACLR) - (Cycling1 Contralateral)	-0.10	1.000
(Cycling2 Contralateral) - (Cycling1 Contralateral)	0.32	0.999
(Gait ACLR) - (Cycling1 Contralateral)	1.81	0.468
(Gait Contralateral) - (Cycling1 Contralateral)	1.11	0.874
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.43	0.998
(Gait ACLR) - (Cycling2 ACLR)	1.91	0.405
(Gait Contralateral) - (Cycling2 ACLR)	1.22	0.826
(Gait ACLR) - (Cycling2 Contralateral)	1.49	0.675
(Gait Contralateral) - (Cycling2 Contralateral)	0.79	0.968
(Gait Contralateral) - (Gait ACLR)	-0.70	0.982

Individual confidence level = 99.54%

Figure C-10: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing maximum FE moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Min FE Moment versus Exercise, Leg

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Exercise	Fixed	3	Cycling1, Cycling2, Gait
Leg	Fixed	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Exercise	2	0.004696	0.002348	5.34	0.008
Leg	1	0.000009	0.000009	0.02	0.889
Exercise*Leg	2	0.000336	0.000168	0.38	0.685
Error	54	0.023735	0.000440		
Total	59	0.028775			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0209653	17.51%	9.88%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.04396	0.00271	-16.24	0.000	
Exercise					
Cycling1	0.01141	0.00383	2.98	0.004	1.33
Cycling2	-0.00126	0.00383	-0.33	0.744	1.33
Leg					
ACLR	0.00038	0.00271	0.14	0.889	1.00
Exercise*Leg					
Cycling1 ACLR	0.00097	0.00383	0.25	0.800	1.33
Cycling2 ACLR	-0.00326	0.00383	-0.85	0.399	1.33

Comparisons for Min FE Moment

Tukey Pairwise Comparisons: Exercise*Leg

Grouping Information Using the Tukey Method and 95% Confidence

Exercise*Leg	N	Mean	Grouping
Cycling1 ACLR	10	-0.0312002	A
Cycling1 Contralateral	10	-0.0339052	A
Cycling2 Contralateral	10	-0.0423432	A
Cycling2 ACLR	10	-0.0480978	A
Gait ACLR	10	-0.0514472	A
Gait Contralateral	10	-0.0567766	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Exercise*Leg Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
(Cycling1 Contralateral) - (Cycling1 ACLR)	-0.00271	0.00938	(-0.03042, 0.02501)	-0.29	1.000
(Cycling2 ACLR) - (Cycling1 ACLR)	-0.01690	0.00938	(-0.04461, 0.01082)	-1.80	0.473
(Cycling2 Contralateral) - (Cycling1 ACLR)	-0.01114	0.00938	(-0.03886, 0.01657)	-1.19	0.840
(Gait ACLR) - (Cycling1 ACLR)	-0.02025	0.00938	(-0.04796, 0.00747)	-2.16	0.274
(Gait Contralateral) - (Cycling1 ACLR)	-0.02558	0.00938	(-0.05329, 0.00214)	-2.73	0.086
(Cycling2 ACLR) - (Cycling1 Contralateral)	-0.01419	0.00938	(-0.04191, 0.01352)	-1.51	0.657
(Cycling2 Contralateral) - (Cycling1 Contralateral)	-0.00844	0.00938	(-0.03615, 0.01927)	-0.90	0.945
(Gait ACLR) - (Cycling1 Contralateral)	-0.01754	0.00938	(-0.04525, 0.01017)	-1.87	0.431
(Gait Contralateral) - (Cycling1 Contralateral)	-0.02287	0.00938	(-0.05058, 0.00484)	-2.44	0.161
(Cycling2 Contralateral) - (Cycling2 ACLR)	0.00575	0.00938	(-0.02196, 0.03347)	0.61	0.990
(Gait ACLR) - (Cycling2 ACLR)	-0.00335	0.00938	(-0.03106, 0.02436)	-0.36	0.999
(Gait Contralateral) - (Cycling2 ACLR)	-0.00868	0.00938	(-0.03639, 0.01903)	-0.93	0.938
(Gait ACLR) - (Cycling2 Contralateral)	-0.00910	0.00938	(-0.03682, 0.01861)	-0.97	0.925
(Gait Contralateral) - (Cycling2 Contralateral)	-0.01443	0.00938	(-0.04215, 0.01328)	-1.54	0.641
(Gait Contralateral) - (Gait ACLR)	-0.00533	0.00938	(-0.03304, 0.02238)	-0.57	0.993

Individual confidence level = 99.54%

Figure C-11: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing minimum FE moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using inverse dynamics (SO).

General Linear Model: Comp-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.1847	0.1847	1.01	0.321
Exercise	2	66.2096	33.1048	181.30	0.000
Knee*Exercise	2	0.0011	0.0005	0.00	0.997
Error	36	6.5733	0.1826		
Total	41	72.9687			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.427309	90.99%	89.74%	87.74%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.9056	0.0659	28.90	0.000	
Knee					
ACLR	-0.0663	0.0659	-1.01	0.321	1.00
Exercise					
C1	-1.0386	0.0932	-11.14	0.000	1.33
C2	-0.7279	0.0932	-7.81	0.000	1.33
Knee*Exercise					
ACLR C1	-0.0070	0.0932	-0.07	0.941	1.33
ACLR C2	0.0023	0.0932	0.02	0.981	1.33

Comparisons for Comp-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping	
Contralateral Gait	7	3.73379	A	
ACLR Gait	7	3.61054	A	
Contralateral C2	7	1.24171		B
ACLR C2	7	1.11366		B
Contralateral C1	7	0.94031		B
ACLR C1	7	0.79374		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value
(ACLR C2) - (ACLR C1)	0.320	0.228	(-0.366, 1.006)	1.40
(ACLR Gait) - (ACLR C1)	2.817	0.228	(2.130, 3.503)	12.33
(Contralateral C1) - (ACLR C1)	0.147	0.228	(-0.540, 0.833)	0.64
(Contralateral C2) - (ACLR C1)	0.448	0.228	(-0.238, 1.134)	1.96
(Contralateral Gait) - (ACLR C1)	2.940	0.228	(2.254, 3.626)	12.87
(ACLR Gait) - (ACLR C2)	2.497	0.228	(1.810, 3.183)	10.93
(Contralateral C1) - (ACLR C2)	-0.173	0.228	(-0.860, 0.513)	-0.76
(Contralateral C2) - (ACLR C2)	0.128	0.228	(-0.558, 0.814)	0.56
(Contralateral Gait) - (ACLR C2)	2.620	0.228	(1.934, 3.307)	11.47
(Contralateral C1) - (ACLR Gait)	-2.670	0.228	(-3.357, -1.984)	-11.69
(Contralateral C2) - (ACLR Gait)	-2.369	0.228	(-3.055, -1.682)	-10.37
(Contralateral Gait) - (ACLR Gait)	0.123	0.228	(-0.563, 0.810)	0.54
(Contralateral C2) - (Contralateral C1)	0.301	0.228	(-0.385, 0.988)	1.32
(Contralateral Gait) - (Contralateral C1)	2.793	0.228	(2.107, 3.480)	12.23
(Contralateral Gait) - (Contralateral C2)	2.492	0.228	(1.806, 3.178)	10.91

Difference of Knee*Exercise Levels	Adjusted P-Value
(ACLR C2) - (ACLR C1)	0.726
(ACLR Gait) - (ACLR C1)	0.000
(Contralateral C1) - (ACLR C1)	0.987
(Contralateral C2) - (ACLR C1)	0.384
(Contralateral Gait) - (ACLR C1)	0.000
(ACLR Gait) - (ACLR C2)	0.000
(Contralateral C1) - (ACLR C2)	0.973
(Contralateral C2) - (ACLR C2)	0.993
(Contralateral Gait) - (ACLR C2)	0.000
(Contralateral C1) - (ACLR Gait)	0.000
(Contralateral C2) - (ACLR Gait)	0.000
(Contralateral Gait) - (ACLR Gait)	0.994
(Contralateral C2) - (Contralateral C1)	0.772
(Contralateral Gait) - (Contralateral C1)	0.000
(Contralateral Gait) - (Contralateral C2)	0.000

Individual confidence level = 99.52%

Figure C-12: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing TF compressive force between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

General Linear Model: Max AP-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.0006	0.0006	0.00	0.961
Exercise	2	20.1431	10.0715	44.37	0.000
Knee*Exercise	2	0.4417	0.2208	0.97	0.388
Error	36	8.1718	0.2270		
Total	41	28.7571			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.476438	71.58%	67.64%	61.32%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	2.0318	0.0735	27.64	0.000	
Knee					
ACLR	-0.0036	0.0735	-0.05	0.961	1.00
Exercise					
C1	0.595	0.104	5.72	0.000	1.33
C2	0.376	0.104	3.62	0.001	1.33
Knee*Exercise					
ACLR C1	-0.106	0.104	-1.02	0.314	1.33
ACLR C2	-0.033	0.104	-0.31	0.756	1.33

Comparisons for Max AP-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping	
Contralateral C1	7	2.73673	A	
ACLR C1	7	2.51725	A	
Contralateral C2	7	2.44405	A	
ACLR C2	7	2.37164	A	
ACLR Gait	7	1.19569		B
Contralateral Gait	7	0.92562		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value
(ACLR C2) - (ACLR C1)	-0.146	0.255	(-0.911, 0.620)	-0.57
(ACLR Gait) - (ACLR C1)	-1.322	0.255	(-2.087, -0.556)	-5.19
(Contralateral C1) - (ACLR C1)	0.219	0.255	(-0.546, 0.985)	0.86
(Contralateral C2) - (ACLR C1)	-0.073	0.255	(-0.839, 0.692)	-0.29
(Contralateral Gait) - (ACLR C1)	-1.592	0.255	(-2.357, -0.826)	-6.25
(ACLR Gait) - (ACLR C2)	-1.176	0.255	(-1.941, -0.411)	-4.62
(Contralateral C1) - (ACLR C2)	0.365	0.255	(-0.400, 1.130)	1.43
(Contralateral C2) - (ACLR C2)	0.072	0.255	(-0.693, 0.838)	0.28
(Contralateral Gait) - (ACLR C2)	-1.446	0.255	(-2.211, -0.681)	-5.68
(Contralateral C1) - (ACLR Gait)	1.541	0.255	(0.776, 2.306)	6.05
(Contralateral C2) - (ACLR Gait)	1.248	0.255	(0.483, 2.014)	4.90
(Contralateral Gait) - (ACLR Gait)	-0.270	0.255	(-1.035, 0.495)	-1.06
(Contralateral C2) - (Contralateral C1)	-0.293	0.255	(-1.058, 0.473)	-1.15
(Contralateral Gait) - (Contralateral C1)	-1.811	0.255	(-2.576, -1.046)	-7.11
(Contralateral Gait) - (Contralateral C2)	-1.518	0.255	(-2.284, -0.753)	-5.96

Difference of Knee*Exercise Levels	Adjusted P-Value
(ACLR C2) - (ACLR C1)	0.992
(ACLR Gait) - (ACLR C1)	0.000
(Contralateral C1) - (ACLR C1)	0.953
(Contralateral C2) - (ACLR C1)	1.000
(Contralateral Gait) - (ACLR C1)	0.000
(ACLR Gait) - (ACLR C2)	0.001
(Contralateral C1) - (ACLR C2)	0.707
(Contralateral C2) - (ACLR C2)	1.000
(Contralateral Gait) - (ACLR C2)	0.000
(Contralateral C1) - (ACLR Gait)	0.000
(Contralateral C2) - (ACLR Gait)	0.000
(Contralateral Gait) - (ACLR Gait)	0.894
(Contralateral C2) - (Contralateral C1)	0.857
(Contralateral Gait) - (Contralateral C1)	0.000
(Contralateral Gait) - (Contralateral C2)	0.000

Individual confidence level = 99.52%

Figure C-13: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing maximum AP shear force between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

General Linear Model: Min AP-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.01499	0.014986	1.24	0.273
Exercise	2	1.99486	0.997430	82.34	0.000
Knee*Exercise	2	0.01921	0.009606	0.79	0.460
Error	36	0.43610	0.012114		
Total	41	2.46516			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.110064	82.31%	79.85%	75.92%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.2555	0.0170	15.04	0.000	
Knee					
ACLR	-0.0189	0.0170	-1.11	0.273	1.00
Exercise					
C1	0.0796	0.0240	3.32	0.002	1.33
C2	0.2180	0.0240	9.08	0.000	1.33
Knee*Exercise					
ACLR C1	-0.0165	0.0240	-0.69	0.496	1.33
ACLR C2	-0.0137	0.0240	-0.57	0.572	1.33

Comparisons for Min AP-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping		
Contralateral C2	7	0.506134	A		
ACLR C2	7	0.440962	A	B	
Contralateral C1	7	0.370519	A	B	
ACLR C1	7	0.299730		B	
ACLR Gait	7	-0.030852			C
Contralateral Gait	7	-0.053479			C

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
(ACLR C2) - (ACLR C1)	0.1412	0.0588	(-0.0356, 0.3180)	2.40	0.183
(ACLR Gait) - (ACLR C1)	-0.3306	0.0588	(-0.5074, -0.1538)	-5.62	0.000
(Contralateral C1) - (ACLR C1)	0.0708	0.0588	(-0.1060, 0.2476)	1.20	0.832
(Contralateral C2) - (ACLR C1)	0.2064	0.0588	(0.0296, 0.3832)	3.51	0.014
(Contralateral Gait) - (ACLR C1)	-0.3532	0.0588	(-0.5300, -0.1764)	-6.00	0.000
(ACLR Gait) - (ACLR C2)	-0.4718	0.0588	(-0.6486, -0.2950)	-8.02	0.000
(Contralateral C1) - (ACLR C2)	-0.0704	0.0588	(-0.2472, 0.1064)	-1.20	0.835
(Contralateral C2) - (ACLR C2)	0.0652	0.0588	(-0.1116, 0.2420)	1.11	0.875
(Contralateral Gait) - (ACLR C2)	-0.4944	0.0588	(-0.6712, -0.3176)	-8.40	0.000
(Contralateral C1) - (ACLR Gait)	0.4014	0.0588	(0.2246, 0.5782)	6.82	0.000
(Contralateral C2) - (ACLR Gait)	0.5370	0.0588	(0.3602, 0.7138)	9.13	0.000
(Contralateral Gait) - (ACLR Gait)	-0.0226	0.0588	(-0.1994, 0.1542)	-0.38	0.999
(Contralateral C2) - (Contralateral C1)	0.1356	0.0588	(-0.0412, 0.3124)	2.31	0.218
(Contralateral Gait) - (Contralateral C1)	-0.4240	0.0588	(-0.6008, -0.2472)	-7.21	0.000
(Contralateral Gait) - (Contralateral C2)	-0.5596	0.0588	(-0.7364, -0.3828)	-9.51	0.000

Individual confidence level = 99.52%

Figure C-14: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing minimum AP shear force between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

General Linear Model: Max ML-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.000620	0.000620	0.54	0.466
Exercise	2	0.004040	0.002020	1.77	0.185
Knee*Exercise	2	0.000421	0.000211	0.18	0.832
Error	36	0.041152	0.001143		
Total	41	0.046234			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0338101	10.99%	0.00%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.12184	0.00522	23.35	0.000	
Knee					
ACLR	0.00384	0.00522	0.74	0.466	1.00
Exercise					
C1	-0.01170	0.00738	-1.59	0.121	1.33
C2	-0.00060	0.00738	-0.08	0.936	1.33
Knee*Exercise					
ACLR C1	-0.00404	0.00738	-0.55	0.587	1.33
ACLR C2	0.00370	0.00738	0.50	0.619	1.33

Comparisons for Max ML-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping
ACLR Gait	7	0.138324	A
Contralateral Gait	7	0.129954	A
ACLR C2	7	0.128784	A
Contralateral C2	7	0.113706	A
Contralateral C1	7	0.110335	A
ACLR C1	7	0.109940	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value
(ACLR C2) - (ACLR C1)	0.0188	0.0181	(-0.0355, 0.0732)	1.04
(ACLR Gait) - (ACLR C1)	0.0284	0.0181	(-0.0259, 0.0827)	1.57
(Contralateral C1) - (ACLR C1)	0.0004	0.0181	(-0.0539, 0.0547)	0.02
(Contralateral C2) - (ACLR C1)	0.0038	0.0181	(-0.0505, 0.0581)	0.21
(Contralateral Gait) - (ACLR C1)	0.0200	0.0181	(-0.0343, 0.0743)	1.11
(ACLR Gait) - (ACLR C2)	0.0095	0.0181	(-0.0448, 0.0639)	0.53
(Contralateral C1) - (ACLR C2)	-0.0184	0.0181	(-0.0728, 0.0359)	-1.02
(Contralateral C2) - (ACLR C2)	-0.0151	0.0181	(-0.0694, 0.0392)	-0.83
(Contralateral Gait) - (ACLR C2)	0.0012	0.0181	(-0.0531, 0.0555)	0.06
(Contralateral C1) - (ACLR Gait)	-0.0280	0.0181	(-0.0823, 0.0263)	-1.55
(Contralateral C2) - (ACLR Gait)	-0.0246	0.0181	(-0.0789, 0.0297)	-1.36
(Contralateral Gait) - (ACLR Gait)	-0.0084	0.0181	(-0.0627, 0.0459)	-0.46
(Contralateral C2) - (Contralateral C1)	0.0034	0.0181	(-0.0509, 0.0577)	0.19
(Contralateral Gait) - (Contralateral C1)	0.0196	0.0181	(-0.0347, 0.0739)	1.09
(Contralateral Gait) - (Contralateral C2)	0.0162	0.0181	(-0.0381, 0.0706)	0.90

Difference of Knee*Exercise Levels	Adjusted P-Value
(ACLR C2) - (ACLR C1)	0.900
(ACLR Gait) - (ACLR C1)	0.622
(Contralateral C1) - (ACLR C1)	1.000
(Contralateral C2) - (ACLR C1)	1.000
(Contralateral Gait) - (ACLR C1)	0.875
(ACLR Gait) - (ACLR C2)	0.995
(Contralateral C1) - (ACLR C2)	0.908
(Contralateral C2) - (ACLR C2)	0.959
(Contralateral Gait) - (ACLR C2)	1.000
(Contralateral C1) - (ACLR Gait)	0.636
(Contralateral C2) - (ACLR Gait)	0.749
(Contralateral Gait) - (ACLR Gait)	0.997
(Contralateral C2) - (Contralateral C1)	1.000
(Contralateral Gait) - (Contralateral C1)	0.884
(Contralateral Gait) - (Contralateral C2)	0.944

Individual confidence level = 99.52%

Figure C-15: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing maximum ML shear force between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

General Linear Model: Min ML-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.000113	0.000113	0.13	0.721
Exercise	2	0.112140	0.056070	63.95	0.000
Knee*Exercise	2	0.000034	0.000017	0.02	0.981
Error	36	0.031565	0.000877		
Total	41	0.143853			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0296110	78.06%	75.01%	70.13%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.01956	0.00457	-4.28	0.000	
Knee					
ACLR	0.00164	0.00457	0.36	0.721	1.00
Exercise					
C1	0.03244	0.00646	5.02	0.000	1.33
C2	0.04048	0.00646	6.27	0.000	1.33
Knee*Exercise					
ACLR C1	-0.00056	0.00646	-0.09	0.931	1.33
ACLR C2	-0.00070	0.00646	-0.11	0.914	1.33

Comparisons for Min ML-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping	
ACLR C2	7	0.0218630	A	
Contralateral C2	7	0.0199825	A	
ACLR C1	7	0.0139631	A	
Contralateral C1	7	0.0118013	A	
ACLR Gait	7	-0.0895790		B
Contralateral Gait	7	-0.0953994		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
(ACLR C2) - (ACLR C1)	0.0079	0.0158	(-0.0397, 0.0555)	0.50	0.996
(ACLR Gait) - (ACLR C1)	-0.1035	0.0158	(-0.1511, -0.0560)	-6.54	0.000
(Contralateral C1) - (ACLR C1)	-0.0022	0.0158	(-0.0497, 0.0454)	-0.14	1.000
(Contralateral C2) - (ACLR C1)	0.0060	0.0158	(-0.0415, 0.0536)	0.38	0.999
(Contralateral Gait) - (ACLR C1)	-0.1094	0.0158	(-0.1569, -0.0618)	-6.91	0.000
(ACLR Gait) - (ACLR C2)	-0.1114	0.0158	(-0.1590, -0.0639)	-7.04	0.000
(Contralateral C1) - (ACLR C2)	-0.0101	0.0158	(-0.0576, 0.0375)	-0.64	0.987
(Contralateral C2) - (ACLR C2)	-0.0019	0.0158	(-0.0494, 0.0457)	-0.12	1.000
(Contralateral Gait) - (ACLR C2)	-0.1173	0.0158	(-0.1648, -0.0697)	-7.41	0.000
(Contralateral C1) - (ACLR Gait)	0.1014	0.0158	(0.0538, 0.1489)	6.41	0.000
(Contralateral C2) - (ACLR Gait)	0.1096	0.0158	(0.0620, 0.1571)	6.92	0.000
(Contralateral Gait) - (ACLR Gait)	-0.0058	0.0158	(-0.0534, 0.0417)	-0.37	0.999
(Contralateral C2) - (Contralateral C1)	0.0082	0.0158	(-0.0394, 0.0557)	0.52	0.995
(Contralateral Gait) - (Contralateral C1)	-0.1072	0.0158	(-0.1548, -0.0596)	-6.77	0.000
(Contralateral Gait) - (Contralateral C2)	-0.1154	0.0158	(-0.1629, -0.0678)	-7.29	0.000

Individual confidence level = 99.52%

Figure C-16: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing minimum ML shear force between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

General Linear Model: Max AA-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.008975	0.008975	7.64	0.009
Exercise	2	0.927966	0.463983	395.02	0.000
Knee*Exercise	2	0.007855	0.003927	3.34	0.047
Error	36	0.042285	0.001175		
Total	41	0.987081			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0342723	95.72%	95.12%	94.17%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.14129	0.00529	26.72	0.000	
Knee					
ACLR	-0.01462	0.00529	-2.76	0.009	1.00
Exercise					
C1	-0.11102	0.00748	-14.84	0.000	1.33
C2	-0.09908	0.00748	-13.25	0.000	1.33
Knee*Exercise					
ACLR C1	0.00937	0.00748	1.25	0.218	1.33
ACLR C2	0.00997	0.00748	1.33	0.191	1.33

Comparisons for Max AA-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping		
Contralateral Gait	7	0.385346	A		
ACLR Gait	7	0.317436		B	
Contralateral C2	7	0.046864			C
ACLR C2	7	0.037567			C
Contralateral C1	7	0.035522			C
ACLR C1	7	0.025020			C

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
(ACLR C2) - (ACLR C1)	0.0125	0.0183	(-0.0425, 0.0676)	0.68	0.983
(ACLR Gait) - (ACLR C1)	0.2924	0.0183	(0.2374, 0.3475)	15.96	0.000
(Contralateral C1) - (ACLR C1)	0.0105	0.0183	(-0.0446, 0.0656)	0.57	0.992
(Contralateral C2) - (ACLR C1)	0.0218	0.0183	(-0.0332, 0.0769)	1.19	0.838
(Contralateral Gait) - (ACLR C1)	0.3603	0.0183	(0.3053, 0.4154)	19.67	0.000
(ACLR Gait) - (ACLR C2)	0.2799	0.0183	(0.2248, 0.3349)	15.28	0.000
(Contralateral C1) - (ACLR C2)	-0.0020	0.0183	(-0.0571, 0.0530)	-0.11	1.000
(Contralateral C2) - (ACLR C2)	0.0093	0.0183	(-0.0458, 0.0644)	0.51	0.996
(Contralateral Gait) - (ACLR C2)	0.3478	0.0183	(0.2927, 0.4028)	18.98	0.000
(Contralateral C1) - (ACLR Gait)	-0.2819	0.0183	(-0.3370, -0.2269)	-15.39	0.000
(Contralateral C2) - (ACLR Gait)	-0.2706	0.0183	(-0.3256, -0.2155)	-14.77	0.000
(Contralateral Gait) - (ACLR Gait)	0.0679	0.0183	(0.0129, 0.1230)	3.71	0.009
(Contralateral C2) - (Contralateral C1)	0.0113	0.0183	(-0.0437, 0.0664)	0.62	0.989
(Contralateral Gait) - (Contralateral C1)	0.3498	0.0183	(0.2948, 0.4049)	19.10	0.000
(Contralateral Gait) - (Contralateral C2)	0.3385	0.0183	(0.2834, 0.3935)	18.48	0.000

Figure C-17: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing maximum AA moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

General Linear Model: Min AA-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.000328	0.000328	0.24	0.629
Exercise	2	0.010956	0.005478	3.95	0.028
Knee*Exercise	2	0.000672	0.000336	0.24	0.786
Error	36	0.049909	0.001386		
Total	41	0.061866			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0372340	19.33%	8.12%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.06675	0.00575	-11.62	0.000	
Knee					
ACLR	-0.00280	0.00575	-0.49	0.629	1.00
Exercise					
C1	0.00672	0.00813	0.83	0.413	1.33
C2	-0.02227	0.00813	-2.74	0.009	1.33
Knee*Exercise					
ACLR C1	0.00526	0.00813	0.65	0.522	1.33
ACLR C2	-0.00082	0.00813	-0.10	0.920	1.33

Comparisons for Min AA-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping
Contralateral Gait	7	-0.0439766	A
ACLR C1	7	-0.0575635	A
ACLR Gait	7	-0.0584362	A
Contralateral C1	7	-0.0624845	A
Contralateral C2	7	-0.0853968	A
ACLR C2	7	-0.0926341	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value
(ACLR C2) - (ACLR C1)	-0.0351	0.0199	(-0.0949, 0.0247)	-1.76
(ACLR Gait) - (ACLR C1)	-0.0009	0.0199	(-0.0607, 0.0589)	-0.04
(Contralateral C1) - (ACLR C1)	-0.0049	0.0199	(-0.0647, 0.0549)	-0.25
(Contralateral C2) - (ACLR C1)	-0.0278	0.0199	(-0.0876, 0.0320)	-1.40
(Contralateral Gait) - (ACLR C1)	0.0136	0.0199	(-0.0462, 0.0734)	0.68
(ACLR Gait) - (ACLR C2)	0.0342	0.0199	(-0.0256, 0.0940)	1.72
(Contralateral C1) - (ACLR C2)	0.0301	0.0199	(-0.0297, 0.0900)	1.51
(Contralateral C2) - (ACLR C2)	0.0072	0.0199	(-0.0526, 0.0670)	0.36
(Contralateral Gait) - (ACLR C2)	0.0487	0.0199	(-0.0112, 0.1085)	2.44
(Contralateral C1) - (ACLR Gait)	-0.0040	0.0199	(-0.0639, 0.0558)	-0.20
(Contralateral C2) - (ACLR Gait)	-0.0270	0.0199	(-0.0868, 0.0329)	-1.35
(Contralateral Gait) - (ACLR Gait)	0.0145	0.0199	(-0.0454, 0.0743)	0.73
(Contralateral C2) - (Contralateral C1)	-0.0229	0.0199	(-0.0827, 0.0369)	-1.15
(Contralateral Gait) - (Contralateral C1)	0.0185	0.0199	(-0.0413, 0.0783)	0.93
(Contralateral Gait) - (Contralateral C2)	0.0414	0.0199	(-0.0184, 0.1012)	2.08

Difference of Knee*Exercise Levels	Adjusted P-Value
(ACLR C2) - (ACLR C1)	0.502
(ACLR Gait) - (ACLR C1)	1.000
(Contralateral C1) - (ACLR C1)	1.000
(Contralateral C2) - (ACLR C1)	0.728
(Contralateral Gait) - (ACLR C1)	0.983
(ACLR Gait) - (ACLR C2)	0.529
(Contralateral C1) - (ACLR C2)	0.657
(Contralateral C2) - (ACLR C2)	0.999
(Contralateral Gait) - (ACLR C2)	0.168
(Contralateral C1) - (ACLR Gait)	1.000
(Contralateral C2) - (ACLR Gait)	0.753
(Contralateral Gait) - (ACLR Gait)	0.977
(Contralateral C2) - (Contralateral C1)	0.856
(Contralateral Gait) - (Contralateral C1)	0.936
(Contralateral Gait) - (Contralateral C2)	0.320

Individual confidence level = 99.52%

Figure C-18: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing minimum AA moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

General Linear Model: Max IE-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.000058	0.000058	0.07	0.794
Exercise	2	0.001684	0.000842	1.00	0.379
Knee*Exercise	2	0.000054	0.000027	0.03	0.968
Error	36	0.030385	0.000844		
Total	41	0.032181			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0290520	5.58%	0.00%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.08110	0.00448	18.09	0.000	
Knee					
ACLR	0.00118	0.00448	0.26	0.794	1.00
Exercise					
C1	0.00627	0.00634	0.99	0.329	1.33
C2	0.00240	0.00634	0.38	0.707	1.33
Knee*Exercise					
ACLR C1	0.00104	0.00634	0.16	0.870	1.33
ACLR C2	0.00054	0.00634	0.09	0.932	1.33

Comparisons for Max IE-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping
ACLR C1	7	0.0895939	A
ACLR C2	7	0.0852213	A
Contralateral C1	7	0.0851568	A
Contralateral C2	7	0.0817825	A
Contralateral Gait	7	0.0728397	A
ACLR Gait	7	0.0720259	A

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
(ACLR C2) - (ACLR C1)	-0.0044	0.0155	(-0.0510, 0.0423)	-0.28	1.000
(ACLR Gait) - (ACLR C1)	-0.0176	0.0155	(-0.0642, 0.0291)	-1.13	0.865
(Contralateral C1) - (ACLR C1)	-0.0044	0.0155	(-0.0511, 0.0422)	-0.29	1.000
(Contralateral C2) - (ACLR C1)	-0.0078	0.0155	(-0.0545, 0.0389)	-0.50	0.996
(Contralateral Gait) - (ACLR C1)	-0.0168	0.0155	(-0.0634, 0.0299)	-1.08	0.887
(ACLR Gait) - (ACLR C2)	-0.0132	0.0155	(-0.0599, 0.0335)	-0.85	0.956
(Contralateral C1) - (ACLR C2)	-0.0001	0.0155	(-0.0467, 0.0466)	-0.00	1.000
(Contralateral C2) - (ACLR C2)	-0.0034	0.0155	(-0.0501, 0.0432)	-0.22	1.000
(Contralateral Gait) - (ACLR C2)	-0.0124	0.0155	(-0.0590, 0.0343)	-0.80	0.966
(Contralateral C1) - (ACLR Gait)	0.0131	0.0155	(-0.0335, 0.0598)	0.85	0.957
(Contralateral C2) - (ACLR Gait)	0.0098	0.0155	(-0.0369, 0.0564)	0.63	0.988
(Contralateral Gait) - (ACLR Gait)	0.0008	0.0155	(-0.0459, 0.0475)	0.05	1.000
(Contralateral C2) - (Contralateral C1)	-0.0034	0.0155	(-0.0500, 0.0433)	-0.22	1.000
(Contralateral Gait) - (Contralateral C1)	-0.0123	0.0155	(-0.0590, 0.0344)	-0.79	0.967
(Contralateral Gait) - (Contralateral C2)	-0.0089	0.0155	(-0.0556, 0.0377)	-0.58	0.992

Individual confidence level = 99.52%

Figure C-19: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing maximum IE moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

General Linear Model: Min IE-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.000322	0.000322	0.67	0.418
Exercise	2	0.038647	0.019324	40.31	0.000
Knee*Exercise	2	0.000943	0.000472	0.98	0.384
Error	36	0.017259	0.000479		
Total	41	0.057171			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0218955	69.81%	65.62%	58.91%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-0.05275	0.00338	-15.61	0.000	
Knee					
ACLR	0.00277	0.00338	0.82	0.418	1.00
Exercise					
C1	0.03790	0.00478	7.93	0.000	1.33
C2	-0.00155	0.00478	-0.33	0.747	1.33
Knee*Exercise					
ACLR C1	-0.00208	0.00478	-0.43	0.666	1.33
ACLR C2	0.00656	0.00478	1.37	0.178	1.33

Comparisons for Min IE-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping		
ACLR C1	7	-0.0141501	A		
Contralateral C1	7	-0.0155342	A		
ACLR C2	7	-0.0449758	A	B	
Contralateral C2	7	-0.0636276		B	C
Contralateral Gait	7	-0.0873867			C
ACLR Gait	7	-0.0908075			C

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
(ACLR C2) - (ACLR C1)	-0.0308	0.0117	(-0.0660, 0.0043)	-2.63	0.115
(ACLR Gait) - (ACLR C1)	-0.0767	0.0117	(-0.1118, -0.0415)	-6.55	0.000
(Contralateral C1) - (ACLR C1)	-0.0014	0.0117	(-0.0366, 0.0338)	-0.12	1.000
(Contralateral C2) - (ACLR C1)	-0.0495	0.0117	(-0.0846, -0.0143)	-4.23	0.002
(Contralateral Gait) - (ACLR C1)	-0.0732	0.0117	(-0.1084, -0.0381)	-6.26	0.000
(ACLR Gait) - (ACLR C2)	-0.0458	0.0117	(-0.0810, -0.0107)	-3.92	0.005
(Contralateral C1) - (ACLR C2)	0.0294	0.0117	(-0.0057, 0.0646)	2.52	0.146
(Contralateral C2) - (ACLR C2)	-0.0187	0.0117	(-0.0538, 0.0165)	-1.59	0.608
(Contralateral Gait) - (ACLR C2)	-0.0424	0.0117	(-0.0776, -0.0072)	-3.62	0.011
(Contralateral C1) - (ACLR Gait)	0.0753	0.0117	(0.0401, 0.1104)	6.43	0.000
(Contralateral C2) - (ACLR Gait)	0.0272	0.0117	(-0.0080, 0.0624)	2.32	0.212
(Contralateral Gait) - (ACLR Gait)	0.0034	0.0117	(-0.0318, 0.0386)	0.29	1.000
(Contralateral C2) - (Contralateral C1)	-0.0481	0.0117	(-0.0833, -0.0129)	-4.11	0.003
(Contralateral Gait) - (Contralateral C1)	-0.0719	0.0117	(-0.1070, -0.0367)	-6.14	0.000
(Contralateral Gait) - (Contralateral C2)	-0.0238	0.0117	(-0.0589, 0.0114)	-2.03	0.346

Individual confidence level = 99.52%

Figure C-20: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing minimum IE moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

General Linear Model: Max FE-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.001137	0.001137	0.77	0.386
Exercise	2	0.037676	0.018838	12.75	0.000
Knee*Exercise	2	0.000650	0.000325	0.22	0.804
Error	36	0.053182	0.001477		
Total	41	0.092644			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0384352	42.60%	34.62%	21.87%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.09174	0.00593	15.47	0.000	
Knee					
ACLR	0.00520	0.00593	0.88	0.386	1.00
Exercise					
C1	0.02744	0.00839	3.27	0.002	1.33
C2	0.01422	0.00839	1.70	0.099	1.33
Knee*Exercise					
ACLR C1	0.00550	0.00839	0.66	0.516	1.33
ACLR C2	-0.00202	0.00839	-0.24	0.811	1.33

Comparisons for Max FE-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping	
ACLR C1	7	0.129882	A	
ACLR C2	7	0.109135	A	B
Contralateral C1	7	0.108475	A	B
Contralateral C2	7	0.102774	A	B
ACLR Gait	7	0.051799		B
Contralateral Gait	7	0.048345		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI
(ACLR C2) - (ACLR C1)	-0.0207	0.0205	(-0.0825, 0.0410)
(ACLR Gait) - (ACLR C1)	-0.0781	0.0205	(-0.1398, -0.0163)
(Contralateral C1) - (ACLR C1)	-0.0214	0.0205	(-0.0831, 0.0403)
(Contralateral C2) - (ACLR C1)	-0.0271	0.0205	(-0.0888, 0.0346)
(Contralateral Gait) - (ACLR C1)	-0.0815	0.0205	(-0.1433, -0.0198)
(ACLR Gait) - (ACLR C2)	-0.0573	0.0205	(-0.1191, 0.0044)
(Contralateral C1) - (ACLR C2)	-0.0007	0.0205	(-0.0624, 0.0611)
(Contralateral C2) - (ACLR C2)	-0.0064	0.0205	(-0.0681, 0.0554)
(Contralateral Gait) - (ACLR C2)	-0.0608	0.0205	(-0.1225, 0.0010)
(Contralateral C1) - (ACLR Gait)	0.0567	0.0205	(-0.0051, 0.1184)
(Contralateral C2) - (ACLR Gait)	0.0510	0.0205	(-0.0108, 0.1127)
(Contralateral Gait) - (ACLR Gait)	-0.0035	0.0205	(-0.0652, 0.0583)
(Contralateral C2) - (Contralateral C1)	-0.0057	0.0205	(-0.0674, 0.0560)
(Contralateral Gait) - (Contralateral C1)	-0.0601	0.0205	(-0.1219, 0.0016)
(Contralateral Gait) - (Contralateral C2)	-0.0544	0.0205	(-0.1162, 0.0073)

Difference of Knee*Exercise Levels	T-Value	Adjusted P-Value
(ACLR C2) - (ACLR C1)	-1.01	0.912
(ACLR Gait) - (ACLR C1)	-3.80	0.007
(Contralateral C1) - (ACLR C1)	-1.04	0.900
(Contralateral C2) - (ACLR C1)	-1.32	0.772
(Contralateral Gait) - (ACLR C1)	-3.97	0.004
(ACLR Gait) - (ACLR C2)	-2.79	0.082
(Contralateral C1) - (ACLR C2)	-0.03	1.000
(Contralateral C2) - (ACLR C2)	-0.31	1.000
(Contralateral Gait) - (ACLR C2)	-2.96	0.056
(Contralateral C1) - (ACLR Gait)	2.76	0.088
(Contralateral C2) - (ACLR Gait)	2.48	0.157
(Contralateral Gait) - (ACLR Gait)	-0.17	1.000
(Contralateral C2) - (Contralateral C1)	-0.28	1.000
(Contralateral Gait) - (Contralateral C1)	-2.93	0.060
(Contralateral Gait) - (Contralateral C2)	-2.65	0.111

Individual confidence level = 99.52%

Figure C-21: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing maximum FE moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

General Linear Model: Min FE-CMC versus Knee, Exercise

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Knee	Fixed	2	ACLR, Contralateral
Exercise	Fixed	3	C1, C2, Gait

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Knee	1	0.000018	0.000018	0.04	0.836
Exercise	2	0.041874	0.020937	51.54	0.000
Knee*Exercise	2	0.000954	0.000477	1.17	0.321
Error	36	0.014623	0.000406		
Total	41	0.057469			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0201543	74.55%	71.02%	65.37%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.00328	0.00311	1.06	0.298	
Knee					
ACLR	-0.00065	0.00311	-0.21	0.836	1.00
Exercise					
C1	0.01877	0.00440	4.27	0.000	1.33
C2	0.02571	0.00440	5.85	0.000	1.33
Knee*Exercise					
ACLR C1	-0.00383	0.00440	-0.87	0.390	1.33
ACLR C2	-0.00289	0.00440	-0.66	0.516	1.33

Comparisons for Min FE-CMC

Tukey Pairwise Comparisons: Knee*Exercise

Grouping Information Using the Tukey Method and 95% Confidence

Knee*Exercise	N	Mean	Grouping	
Contralateral C2	7	0.0325282	A	
Contralateral C1	7	0.0265280	A	
ACLR C2	7	0.0254552	A	
ACLR C1	7	0.0175717	A	
ACLR Gait	7	-0.0351199		B
Contralateral Gait	7	-0.0472604		B

Means that do not share a letter are significantly different.

Tukey Simultaneous Tests for Differences of Means

Difference of Knee*Exercise Levels	Difference of Means	SE of Difference	Simultaneous 95% CI	T-Value	Adjusted P-Value
(ACLR C2) - (ACLR C1)	0.0079	0.0108	(-0.0245, 0.0403)	0.73	0.977
(ACLR Gait) - (ACLR C1)	-0.0527	0.0108	(-0.0851, -0.0203)	-4.89	0.000
(Contralateral C1) - (ACLR C1)	0.0090	0.0108	(-0.0234, 0.0413)	0.83	0.960
(Contralateral C2) - (ACLR C1)	0.0150	0.0108	(-0.0174, 0.0473)	1.39	0.734
(Contralateral Gait) - (ACLR C1)	-0.0648	0.0108	(-0.0972, -0.0325)	-6.02	0.000
(ACLR Gait) - (ACLR C2)	-0.0606	0.0108	(-0.0929, -0.0282)	-5.62	0.000
(Contralateral C1) - (ACLR C2)	0.0011	0.0108	(-0.0313, 0.0334)	0.10	1.000
(Contralateral C2) - (ACLR C2)	0.0071	0.0108	(-0.0253, 0.0394)	0.66	0.986
(Contralateral Gait) - (ACLR C2)	-0.0727	0.0108	(-0.1051, -0.0403)	-6.75	0.000
(Contralateral C1) - (ACLR Gait)	0.0616	0.0108	(0.0293, 0.0940)	5.72	0.000
(Contralateral C2) - (ACLR Gait)	0.0676	0.0108	(0.0353, 0.1000)	6.28	0.000
(Contralateral Gait) - (ACLR Gait)	-0.0121	0.0108	(-0.0445, 0.0202)	-1.13	0.867
(Contralateral C2) - (Contralateral C1)	0.0060	0.0108	(-0.0264, 0.0384)	0.56	0.993
(Contralateral Gait) - (Contralateral C1)	-0.0738	0.0108	(-0.1062, -0.0414)	-6.85	0.000
(Contralateral Gait) - (Contralateral C2)	-0.0798	0.0108	(-0.1122, -0.0474)	-7.41	0.000

Individual confidence level = 99.52%

Figure C-22: Statistical summary of two-way ANOVA test and post-hoc Tukey test comparing minimum FE moment between gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) for the ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics (CMC).

APPENDIX D: Joint Reaction Analysis Results Using Computed Muscle Control

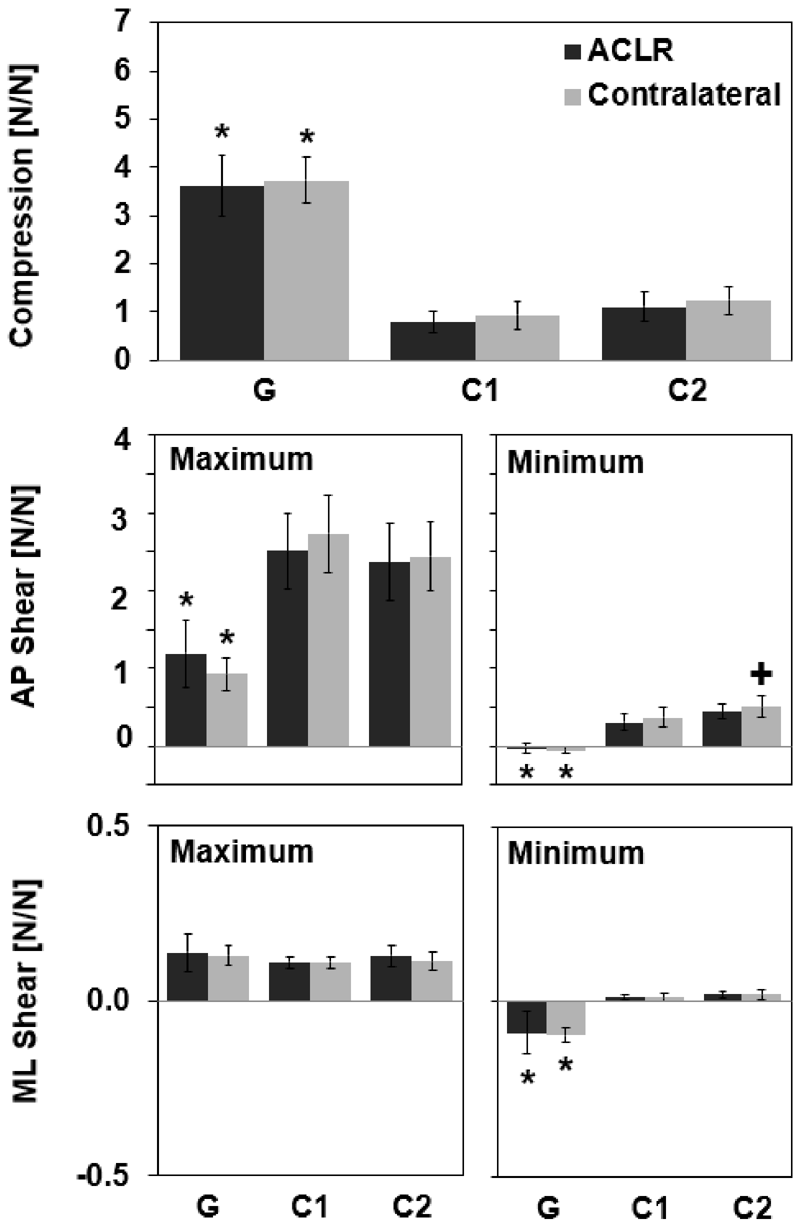

Figure D-1: Comparison of knee joint contact forces between gait (G), cycling at moderate resistance (C1), and cycling at high resistance (C2) for ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics analysis. Positive AP and ML shear forces are anteriorly and medially directed, respectively. * = significantly different than both ACLR and contralateral results for C1 and C2 ($p<0.05$); + = significantly different than results from ACLR C1 ($p<0.05$).

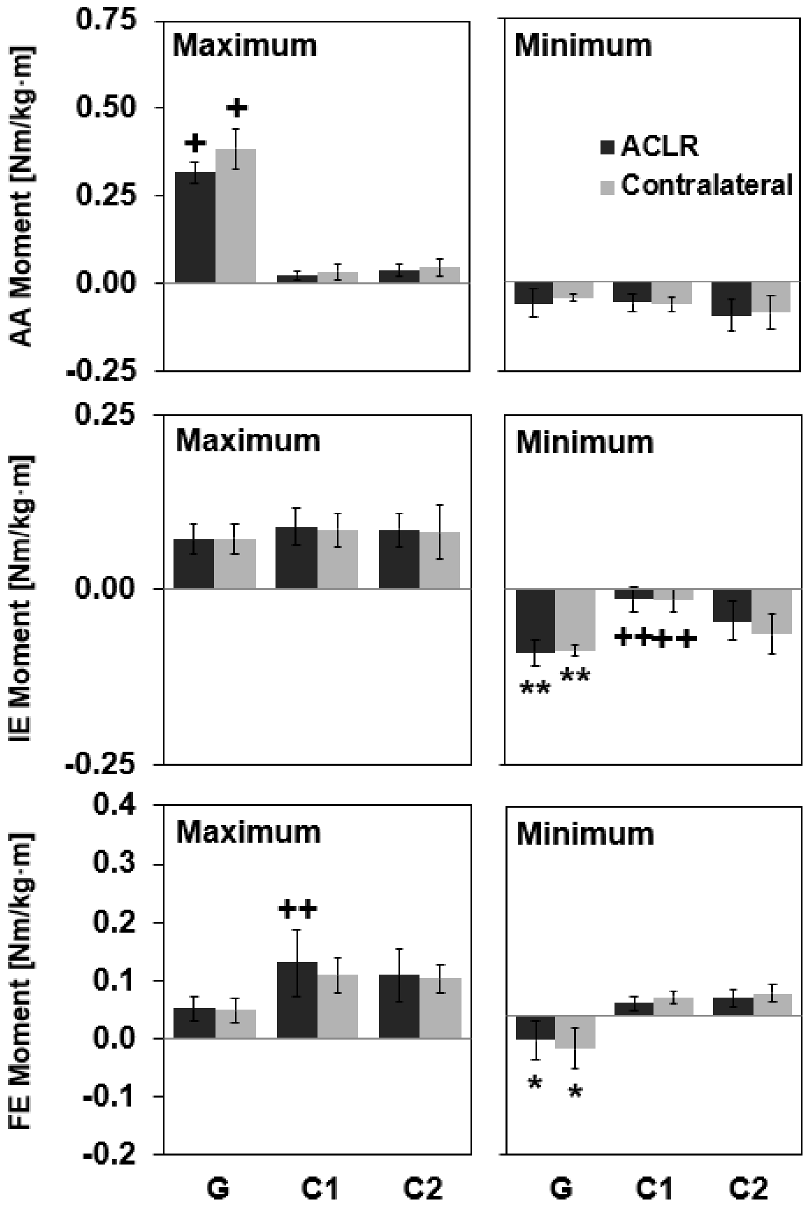

Figure D-2: Comparison of knee joint contact moments between gait (G), cycling at moderate resistance (C1), and cycling at high resistance (C2) for ACL reconstructed (ACLR) and contralateral knees using EMG-driven inverse dynamics analysis. Positive AA, IE, and FE are abduction, internal, and flexion directed moments. * = significantly different than both ACLR and contralateral results for C1 and C2 ($p<0.05$); + = significantly different than all other groups ($p<0.05$); ** = significantly different than both ACLR and contralateral results for C1 and ACLR results for C2 ($p<0.05$); ++ = significantly different than both ACLR and contralateral results for G ($p<0.05$).

Table D-1: Summary of maximum average knee joint contact forces and moments obtained from joint reaction analysis for ACLR and Contralateral knees during Gait (G), Cycling Resistance 1, (C1), and Cycling Resistance 2 (C2) training (n=10) using EMG-driven inverse dynamics.

Maximum		G	C1	C2
AP Force	ACLR	1.196 ± 0.435	2.517 ± 0.486	2.372 ± 0.500
	Contralateral	0.926 ± 0.210	2.737 ± 0.501	2.444 ± 0.444
Comp Force	ACLR	1.611 0.624	0.794 ± 0.235	1.114 ± 0.318
	Contralateral	3.734 ± 0.473	0.940 ± 0.294	1.242 ± 0.289
ML Force	ACLR	0.138 ± 0.056	0.110 ± 0.015	0.129 ± 0.029
	Contralateral	0.130 ± 0.029	0.110 ± 0.016	0.114 ± 0.025
AA Moment	ACLR	0.317 ± 0.031	0.025 ± 0.012	0.038 ± 0.018
	Contralateral	0.385 ± 0.058	0.036 ± 0.023	0.047 ± 0.025
IE Moment	ACLR	0.072 ± 0.022	0.090 ± 0.027	0.085 ± 0.024
	Contralateral	0.073 ± 0.021	0.085 ± 0.024	0.082 ± 0.039
FE Moment	ACLR	0.052 ± 0.021	0.130 ± 0.056	0.109 ± 0.045
	Contralateral	0.048 ± 0.022	0.108 ± 0.030	0.103 ± 0.024

Table D-2: Summary of minimum average knee joint contact forces and moments obtained from joint reaction analysis for ACLR and Contralateral knees during Gait (G), Cycling Resistance 1, (C1), and Cycling Resistance 2 (C2) training (n=10) using EMG-driven inverse dynamics.

Minimum		G	C1	C2
AP Force	ACLR	-0.031 ± 0.068	0.300 ± 0.105	0.441 ± 0.092
	Contralateral	-0.053 ± 0.041	0.371 ± 0.131	0.506 ± 0.139
Comp Force	ACLR	0.262 ± 0.073	-0.032 ± 0.193	0.056 ± 0.172
	Contralateral	0.250 ± 0.090	0.043 ± 0.166	0.053 ± 0.178
ML Force	ACLR	-0.090 ± 0.060	0.014 ± 0.008	0.022 ± 0.020
	Contralateral	-0.095 ± 0.021	0.012 ± 0.012	0.020 ± 0.012
AA Moment	ACLR	-0.058 ± 0.041	-0.058 ± 0.023	-0.093 ± 0.046
	Contralateral	-0.044 ± 0.011	-0.062 ± 0.021	-0.085 ± 0.047
IE Moment	ACLR	-0.091 ± 0.018	-0.014 ± 0.017	-0.045 ± 0.027
	Contralateral	-0.087 ± 0.008	-0.016 ± 0.016	-0.064 ± 0.028
FE Moment	ACLR	-0.035 ± 0.027	0.018 ± 0.010	0.025 ± 0.012
	Contralateral	-0.047 ± 0.029	0.027 ± 0.010	0.033 ± 0.012

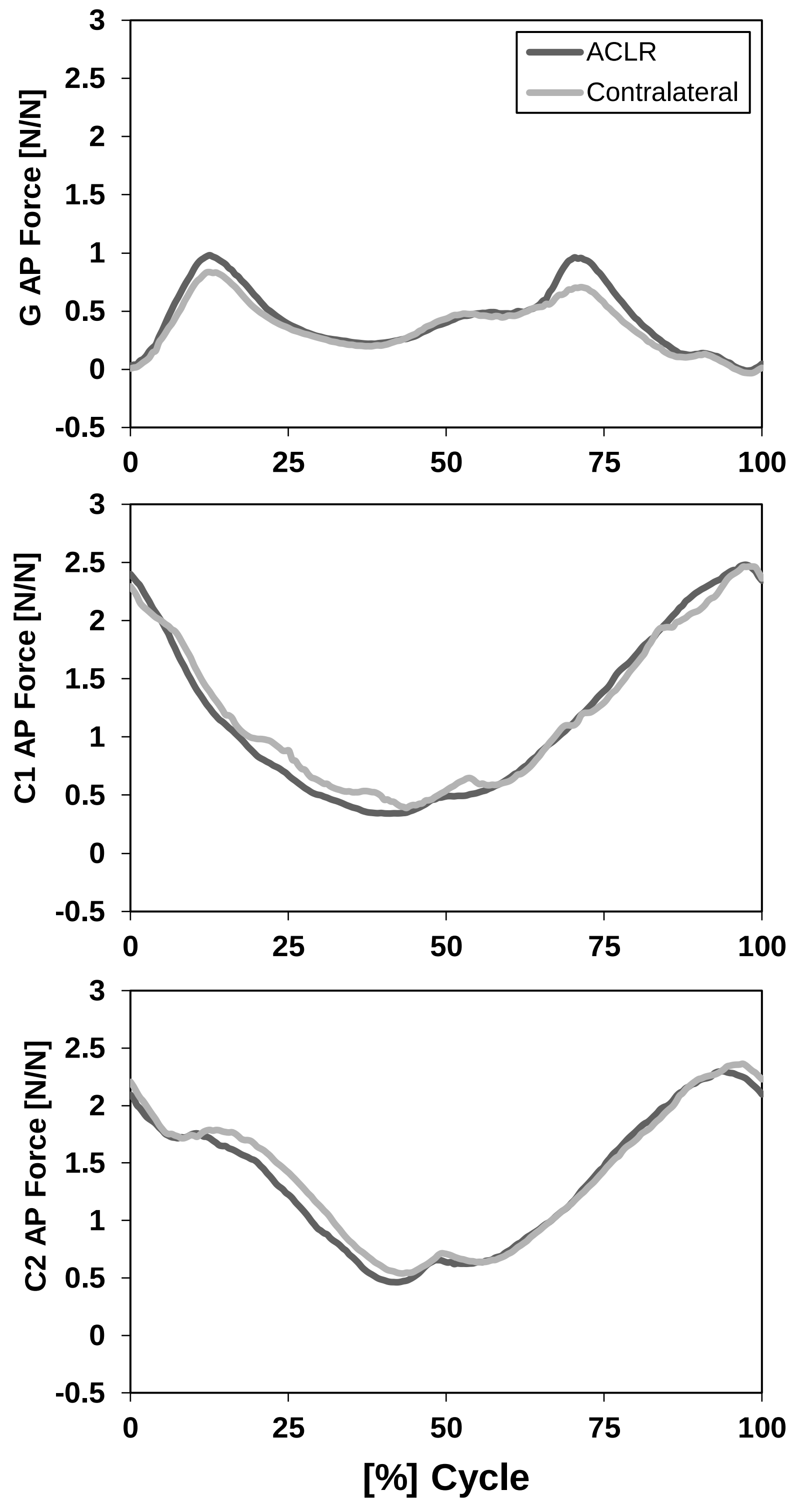

Figure D-3: Average anterior(+)-posterior(-) knee joint contact force during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=7).

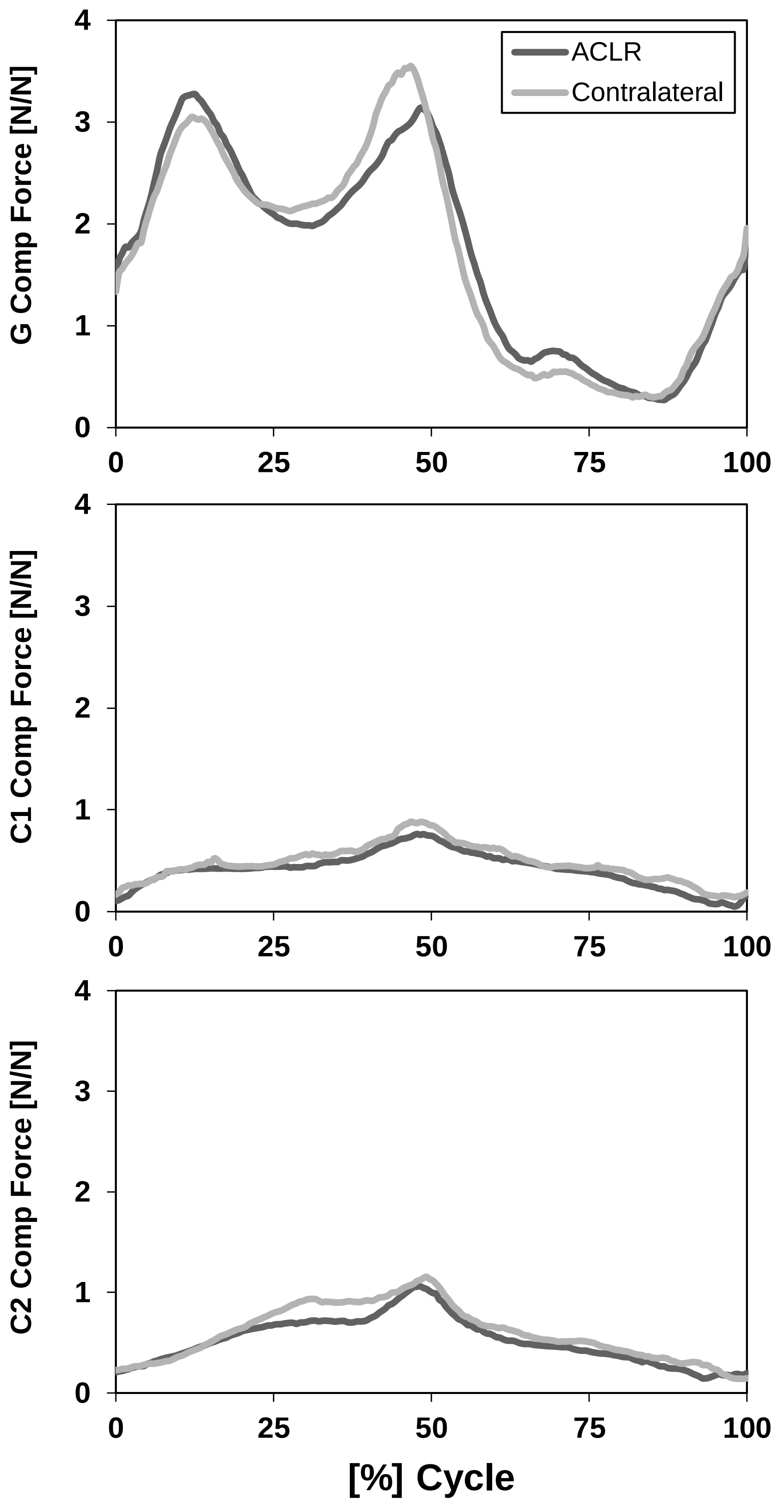

Figure D-4: Average compressive knee joint contact force during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=7).

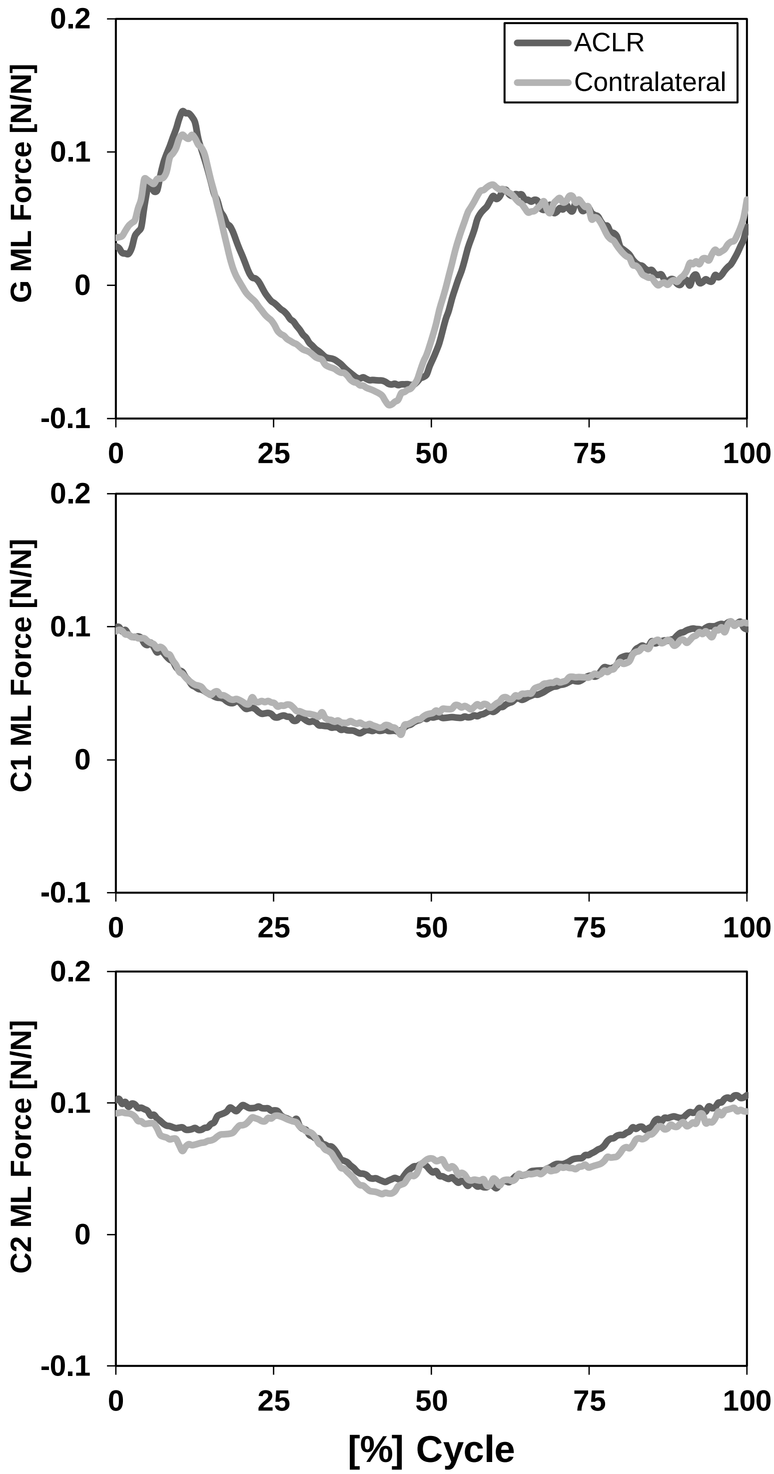

Figure D-5: Average medial(+)-lateral(-) knee joint contact force during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=7).

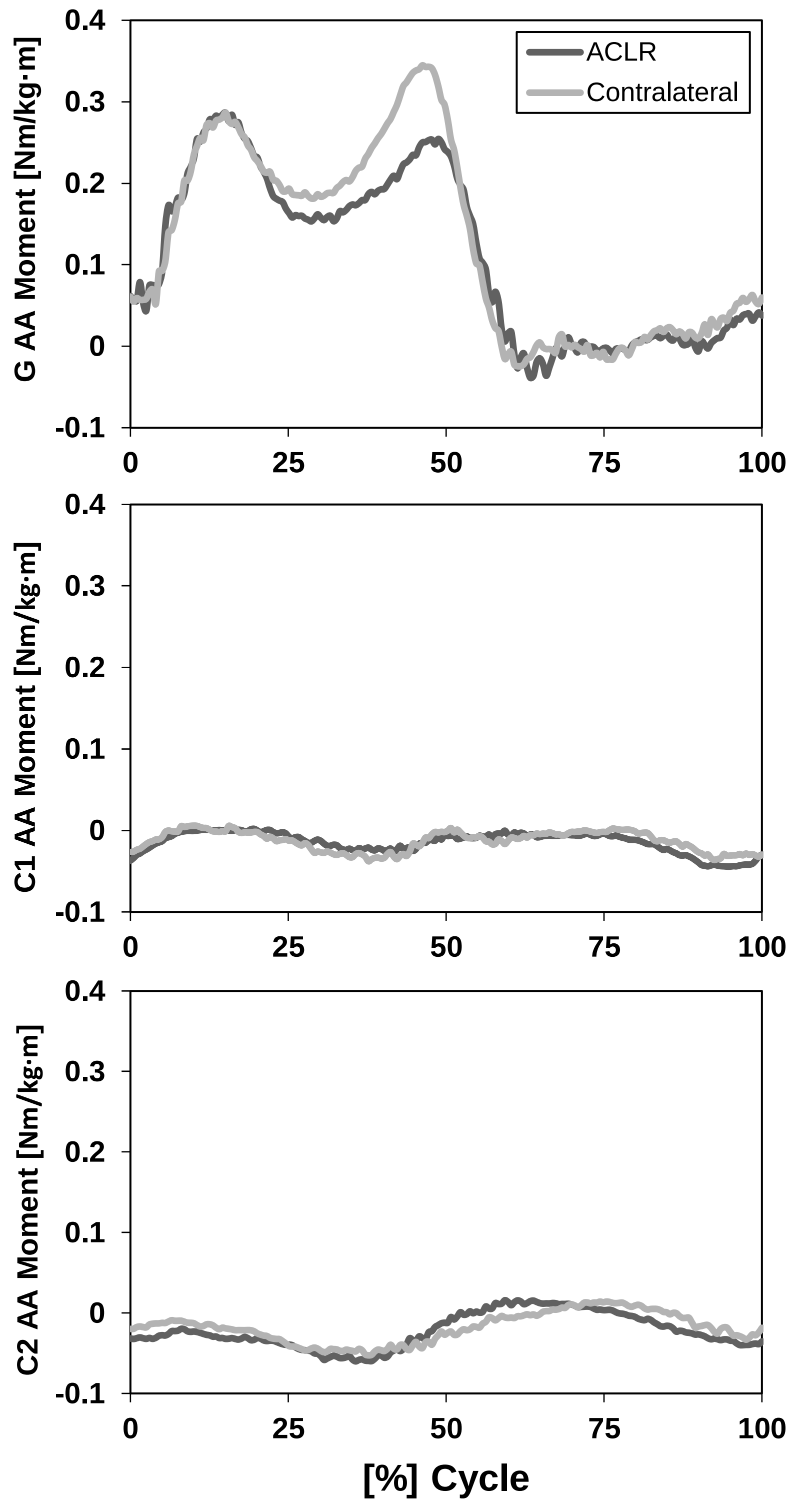

Figure D-6: Average abduction(+)-adduction(-) knee joint contact moment during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=7).

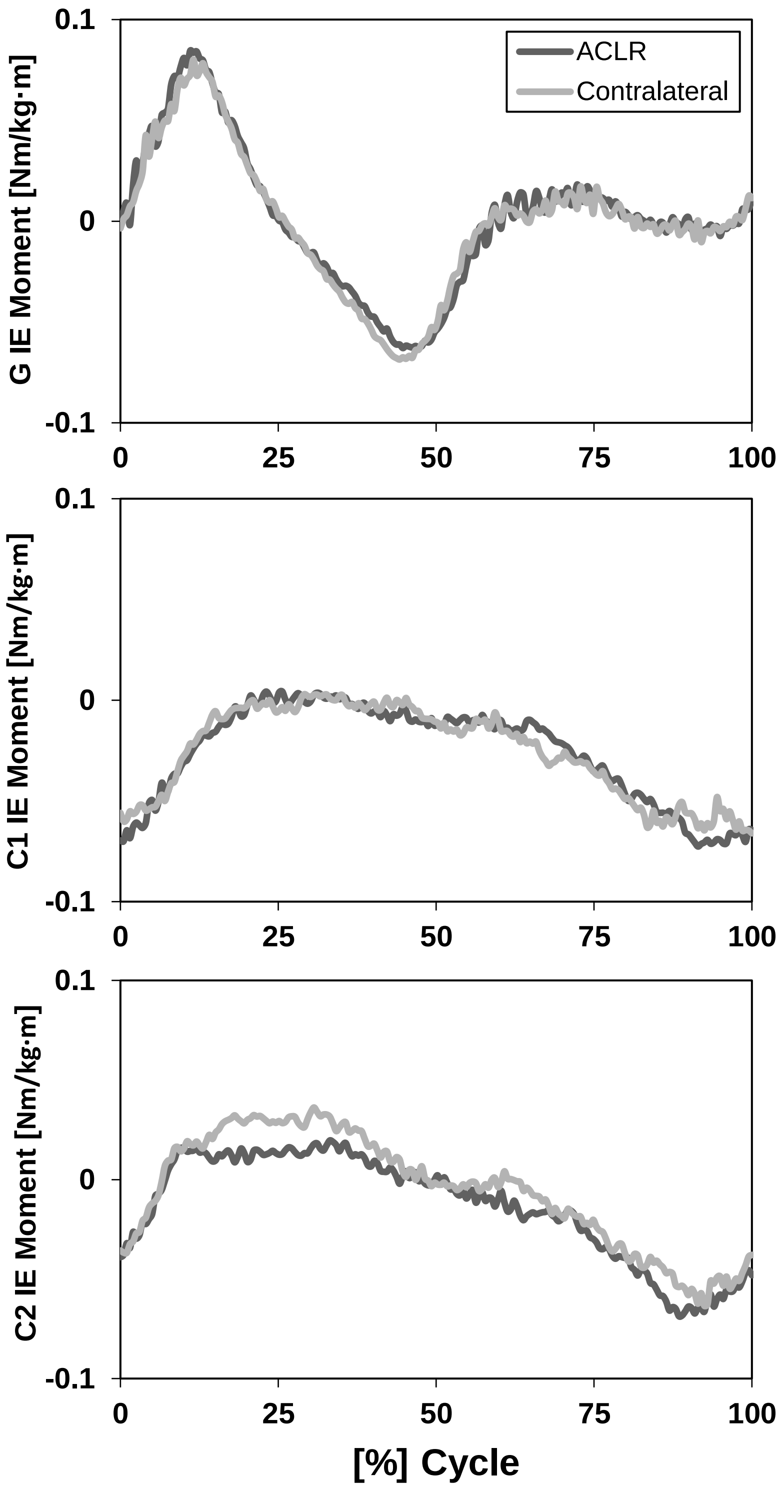

Figure D-7: Average internal(+)-external(-) rotation knee joint contact moment during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=7).

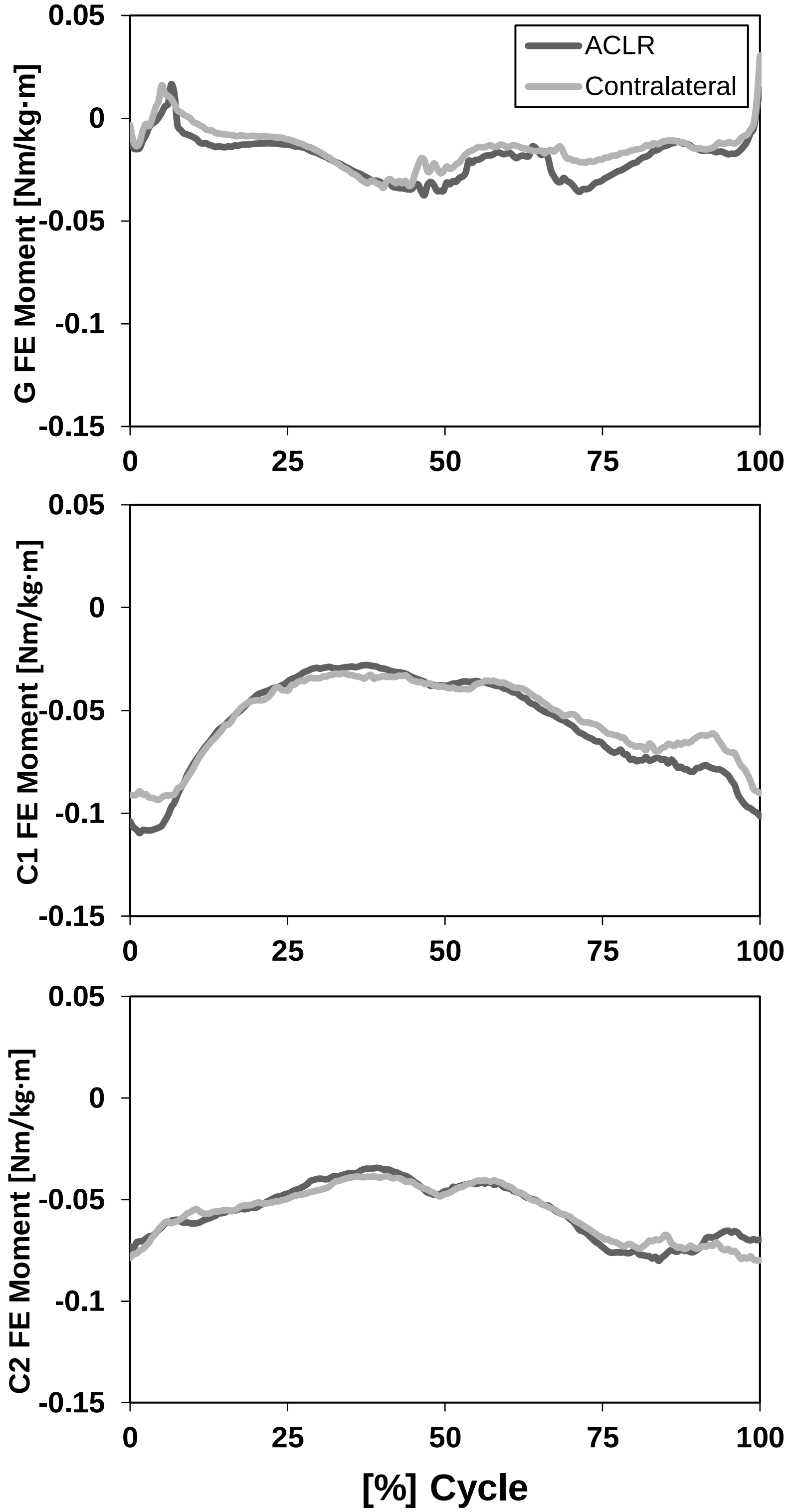

Figure D-8: Average flexion(+)-extension(-) knee joint contact moment during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training (n=7).

APPENDIX E: Comparison of Joint Reaction Results Using Inverse Dynamics (SO) and EMG-Driven Inverse Dynamics (CMC)

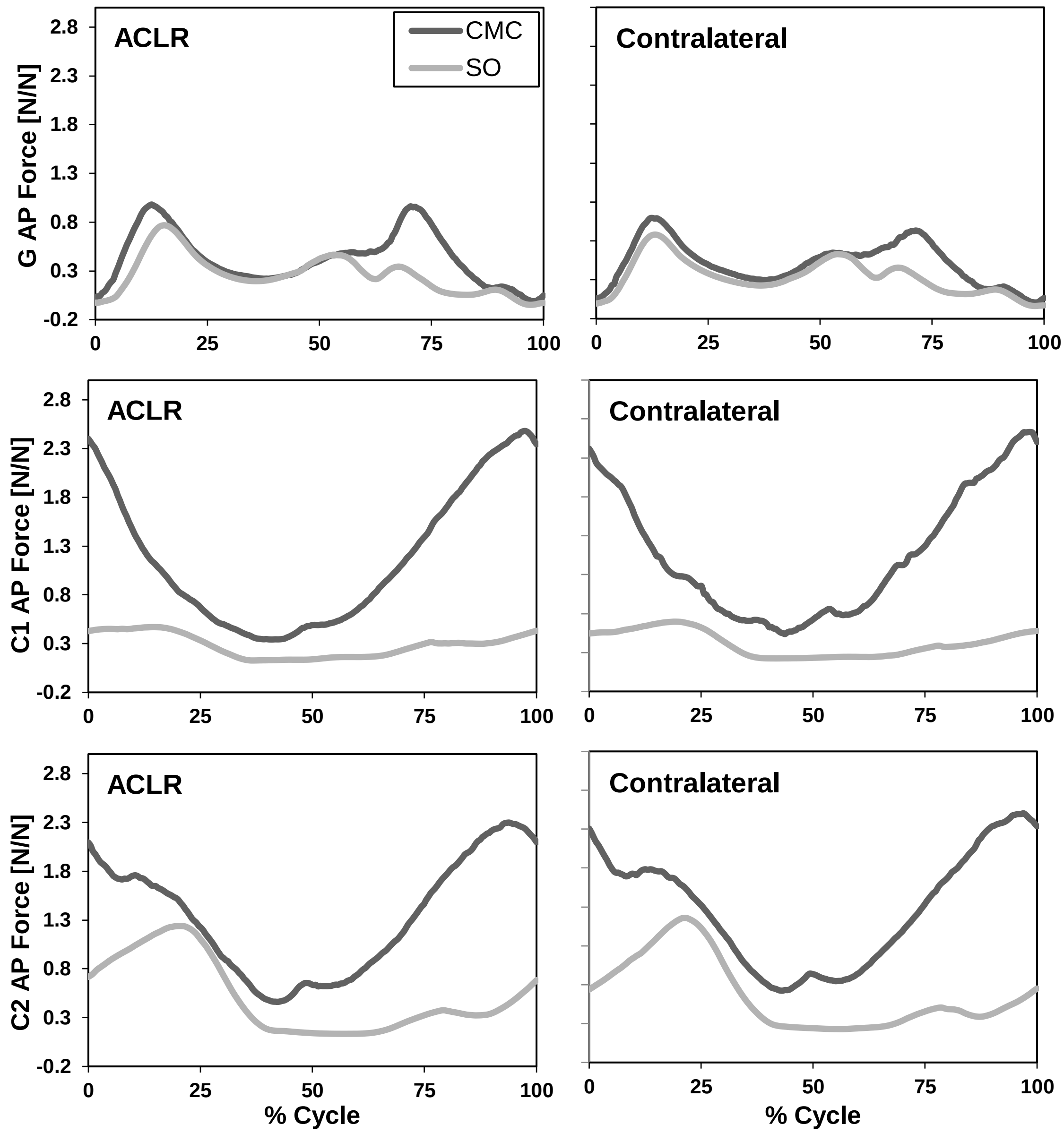

Figure E-1: Average anterior(+)-posterior(-) knee joint contact force during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training using EMG-driven inverse dynamics (CMC) and inverse dynamics (SO) (n=7).

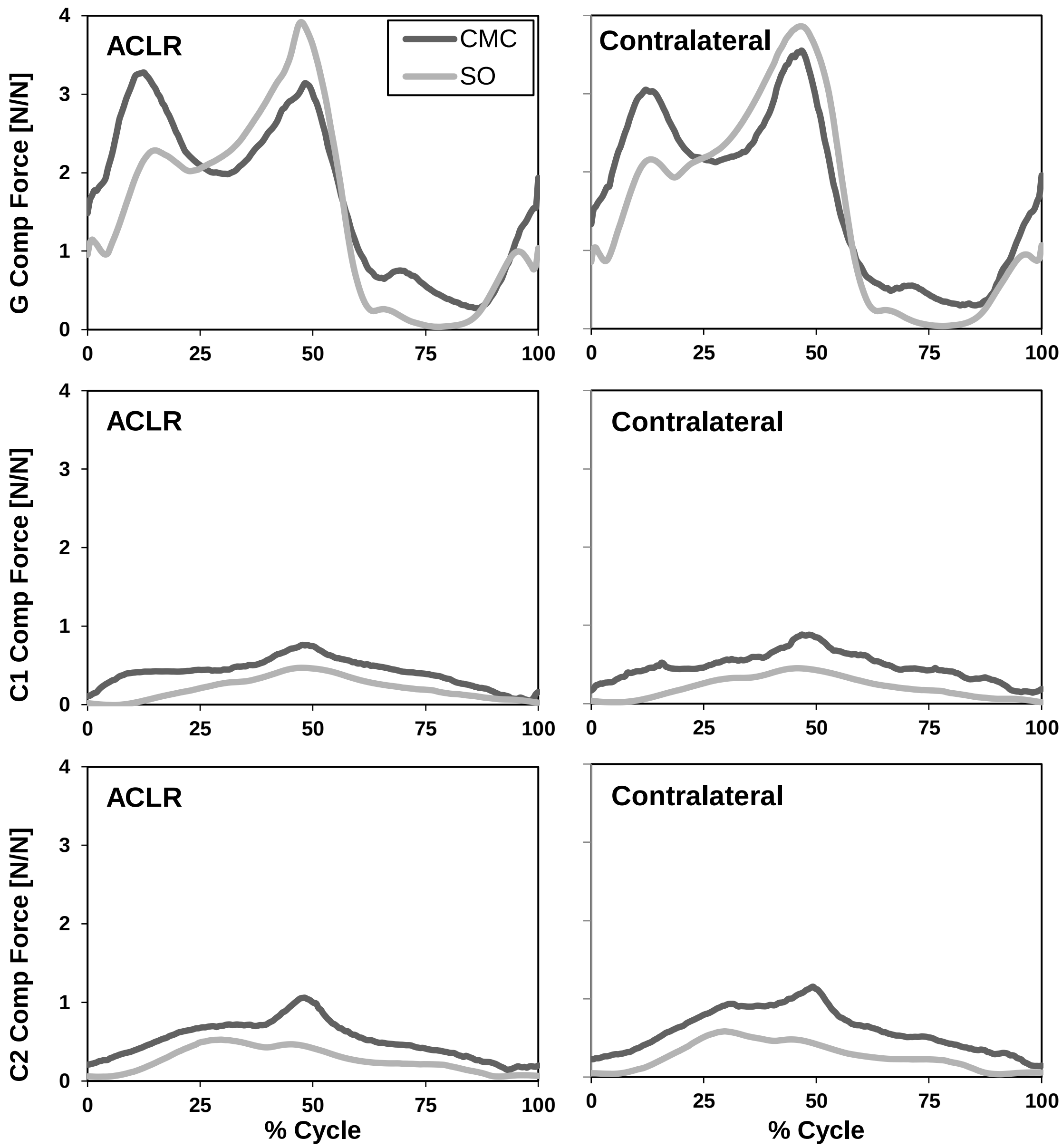

Figure E-2: Average compressive knee joint contact force during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training using EMG-driven inverse dynamics (CMC) and inverse dynamics (SO) (n=7).

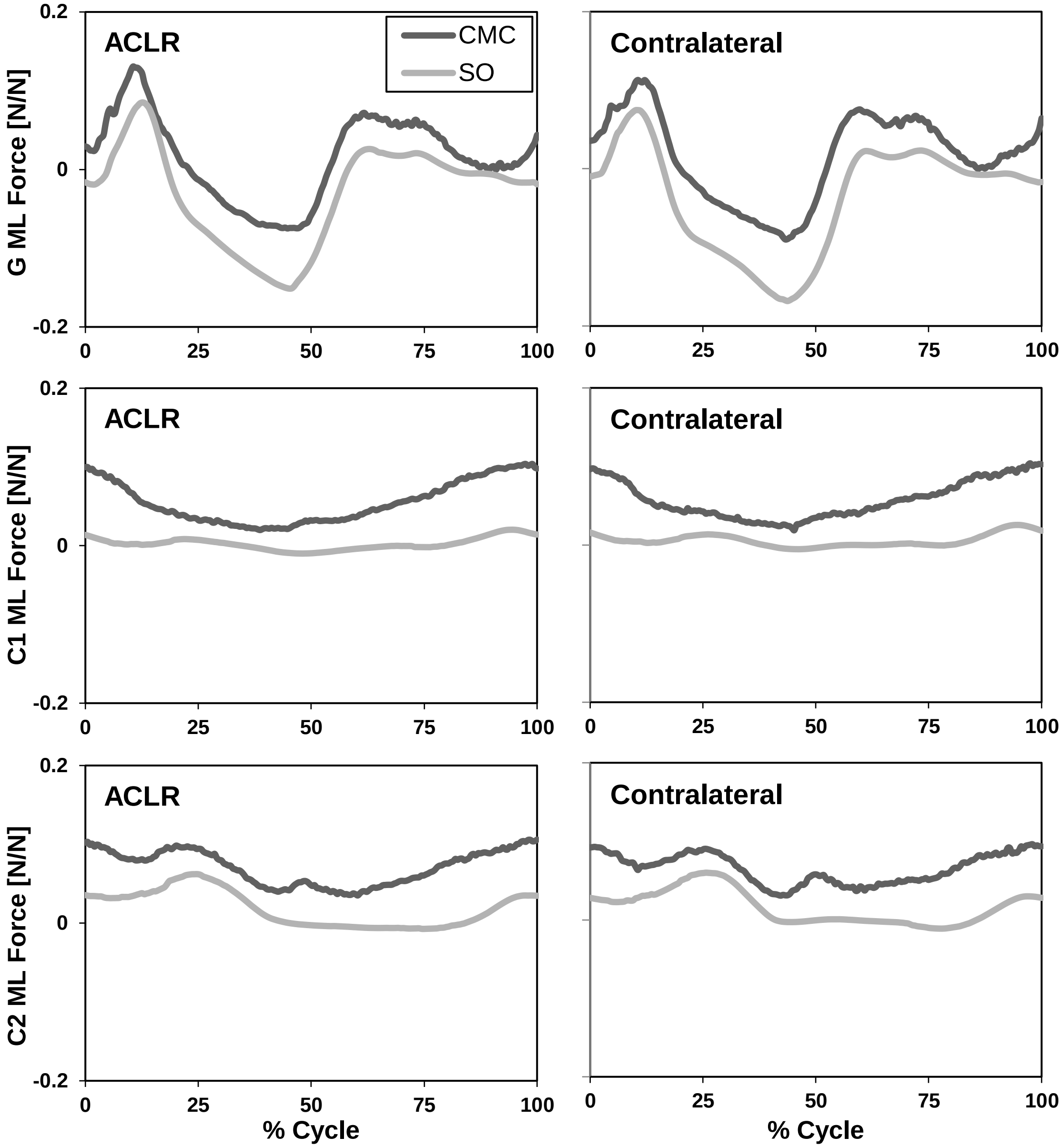

Figure E-3: Average medial(+)-lateral(-) knee joint contact force during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training using EMG-driven inverse dynamics (CMC) and inverse dynamics (SO) (n=7).

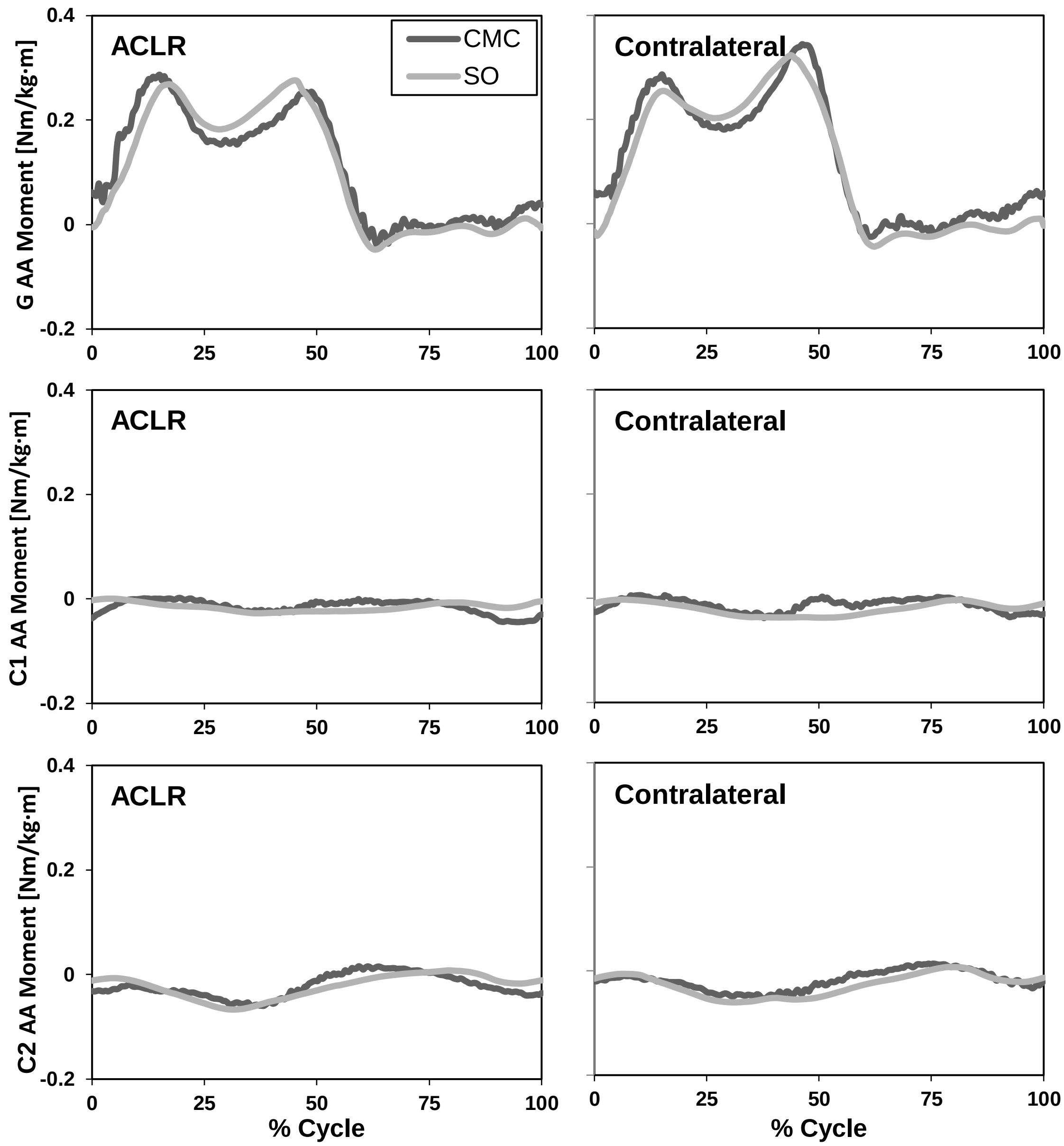

Figure E-4: Average abduction(+)-adduction(-) knee joint contact moment during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training using EMG-driven inverse dynamics (CMC) and inverse dynamics (SO) (n=7).

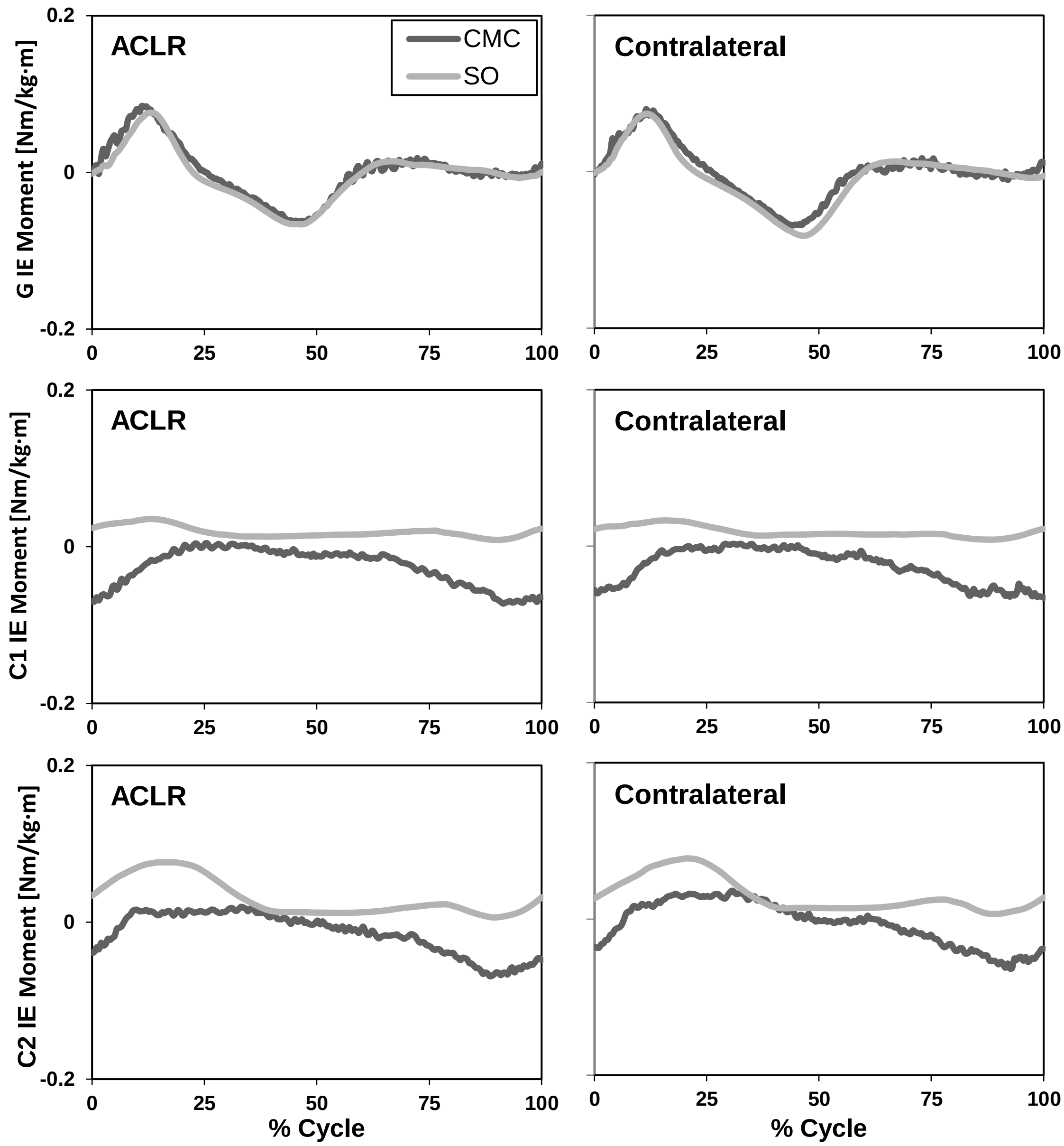

Figure E-5: Average internal(+)-external(-) rotation knee joint contact moment during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training using EMG-driven inverse dynamics (CMC) and inverse dynamics (SO) (n=7).

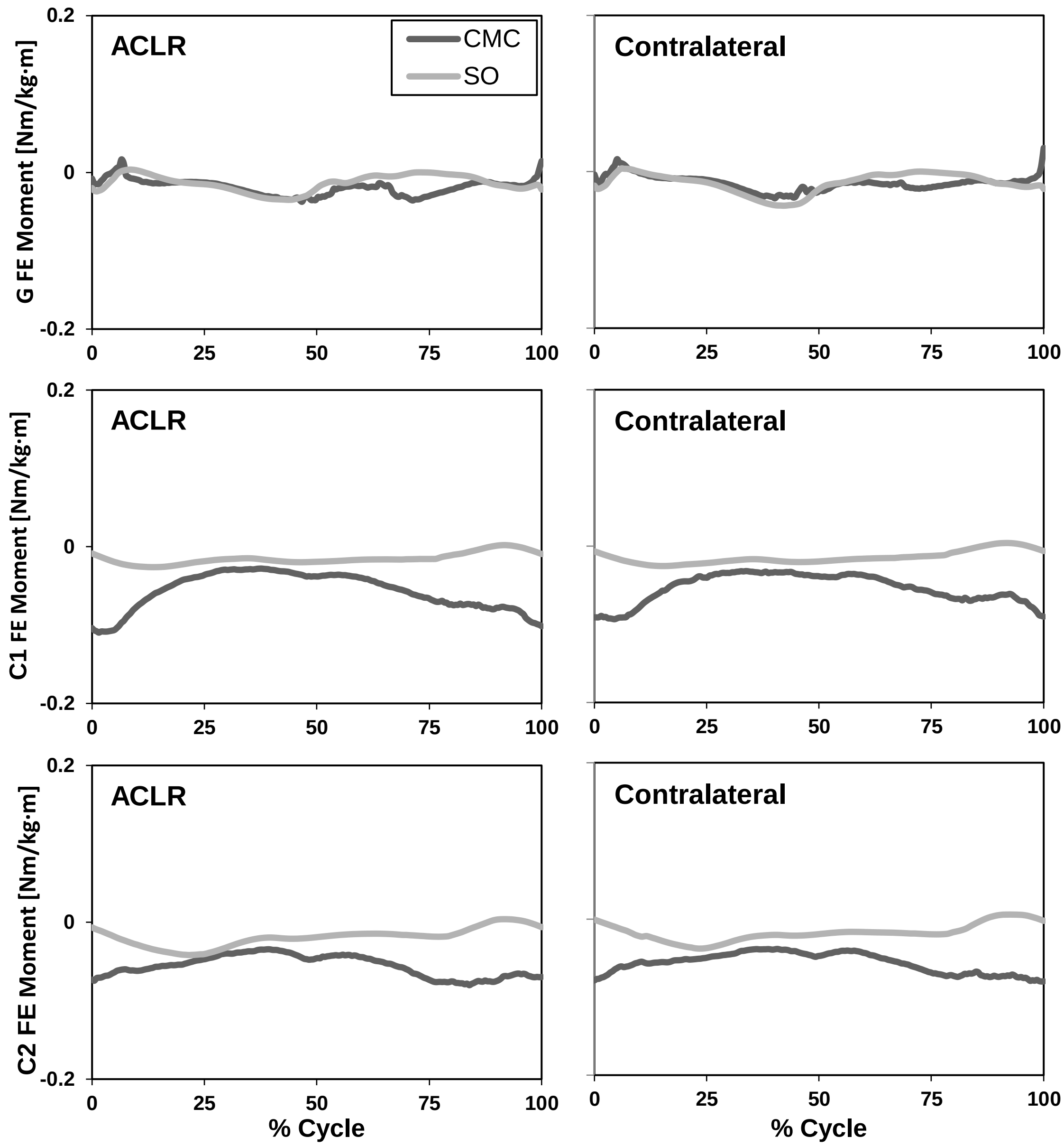

Figure E-6: Average flexion(+)-extension(-) knee joint contact moment during gait (G), cycling at a moderate resistance (C1), and cycling at a high resistance (C2) training using EMG-driven inverse dynamics (CMC) and inverse dynamics (SO) (n=7).

APPENDIX F: Statistical Summary Comparing CMC and SO Results

Table F-1: Paired t-test results comparing maximum and minimum forces and moments obtained from inverse dynamics (SO) and EMG-driven inverse dynamics (CMC). *Significance defined by p<0.05.

Load	P-Value
TF Compressive	0.072
Max AP Shear	<0.001*
Min AP Shear	<0.001*
Max ML Shear	<0.001*
Min ML Shear	<0.001*
Max AA Moment	<0.001*
Min AA Moment	0.383
Max IE Moment	<0.001*
Min IE Moment	0.003*
Max FE Moment	<0.001*
Min Fe Moment	0.036*

Paired T-Test and CI: Comp-CMC, Comp-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Comp-CMC	42	1.906	1.334	0.206
Comp-SO	42	1.715	1.767	0.273

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
0.191	0.668	0.103	(-0.018, 0.399)

μ_difference: mean of (Comp-CMC - Comp-SO)

Test

Null hypothesis H$_0$: μ_difference = 0
Alternative hypothesis H$_1$: μ_difference ≠ 0

T-Value	P-Value
1.85	0.072

Figure F-1: Results of paired t-test comparing difference in TF ompressive using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

Paired T-Test and CI: Max AP-CMC, Max AP-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Max AP-CMC	42	2.032	0.837	0.129
Max AP-SO	42	0.920	0.439	0.068

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
1.112	0.873	0.135	(0.840, 1.384)

μ_difference: mean of (Max AP-CMC - Max AP-SO)

Test

Null hypothesis	H_0: μ_difference = 0
Alternative hypothesis	H_1: μ_difference ≠ 0

T-Value	P-Value
8.26	0.000

Figure F-2: Results of paired t-test comparing difference in maximum AP shear using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

Paired T-Test and CI: Min AP-CMC, Min AP-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Min AP-CMC	42	0.2555	0.2452	0.0378
Min AP-SO	42	0.0441	0.0872	0.0135

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
0.2114	0.1717	0.0265	(0.1579, 0.2649)

μ_difference: mean of (Min AP-CMC - Min AP-SO)

Test

Null hypothesis	H_0: μ_difference = 0
Alternative hypothesis	H_1: μ_difference ≠ 0

T-Value	P-Value
7.98	0.000

Figure F-3: Results of paired t-test comparing difference in minimum AP shear using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

Paired T-Test and CI: Max ML-CMC, Max ML-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Max ML-CMC	42	0.12184	0.03358	0.00518
Max ML-SO	42	0.06148	0.04551	0.00702

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
0.06036	0.02881	0.00444	(0.05138, 0.06934)

μ_difference: mean of (Max ML-CMC - Max ML-SO)

Test

Null hypothesis H_0: μ_difference = 0
Alternative hypothesis H_1: μ_difference ≠ 0

T-Value	P-Value
13.58	0.000

Figure F-4: Results of paired t-test comparing difference in maximum ML shear using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

Paired T-Test and CI: Min ML-CMC, Min ML-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Min ML-CMC	42	-0.0196	0.0592	0.0091
Min ML-SO	42	-0.0655	0.0769	0.0119

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
0.04590	0.02570	0.00397	(0.03789, 0.05391)

μ_difference: mean of (Min ML-CMC - Min ML-SO)

Test

Null hypothesis H_0: μ_difference = 0
Alternative hypothesis H_1: μ_difference ≠ 0

T-Value	P-Value
11.57	0.000

Figure F-5: Results of paired t-test comparing difference in minimum ML shear using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

Paired T-Test and CI: Max AA-CMC, Max AA-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Max AA-CMC	42	0.1413	0.1552	0.0239
Max AA-SO	42	0.1154	0.1467	0.0226

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
0.02586	0.02698	0.00416	(0.01745, 0.03426)

μ_difference: mean of (Max AA-CMC - Max AA-SO)

Test

Null hypothesis H₀: μ_difference = 0
Alternative hypothesis H₁: μ_difference ≠ 0

T-Value	P-Value
6.21	0.000

Figure F-6: Results of paired t-test comparing difference in maximum AA moment using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

Paired T-Test and CI: Min AA-CMC, Min AA-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Min AA-CMC	42	-0.06675	0.03884	0.00599
Min AA-SO	42	-0.06277	0.03890	0.00600

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
-0.00398	0.02928	0.00452	(-0.01310, 0.00514)

μ_difference: mean of (Min AA-CMC - Min AA-SO)

Test

Null hypothesis H_0: μ_difference = 0
Alternative hypothesis H_1: μ_difference ≠ 0

T-Value	P-Value
-0.88	0.383

Figure F-7: Results of paired t-test comparing difference in minimum AA moment using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

Paired T-Test and CI: Max IE-CMC, Max IE-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Max IE-CMC	42	0.08110	0.02802	0.00432
Max IE-SO	42	0.02375	0.04004	0.00618

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
0.05735	0.05125	0.00791	(0.04138, 0.07332)

μ_difference: mean of (Max IE-CMC - Max IE-SO)

Test

Null hypothesis H_0: μ_difference = 0
Alternative hypothesis H_1: μ_difference ≠ 0

T-Value	P-Value
7.25	0.000

Figure F-8: Results of paired t-test comparing difference in maximum IE moment using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

Paired T-Test and CI: Min IE-CMC, Min IE-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Min IE-CMC	42	-0.05275	0.03734	0.00576
Min IE-SO	42	-0.06766	0.02685	0.00414

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
0.01491	0.03039	0.00469	(0.00544, 0.02439)

μ_difference: mean of (Min IE-CMC - Min IE-SO)

Test

Null hypothesis H_0: μ_difference = 0
Alternative hypothesis H_1: μ_difference ≠ 0

T-Value	P-Value
3.18	0.003

Figure F-9: Results of paired t-test comparing difference in maximum IE moment using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

Paired T-Test and CI: Max FE-CMC, Max FE-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Max FE-CMC	42	0.09174	0.04754	0.00733
Max FE-SO	42	0.04158	0.02221	0.00343

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for µ_difference
0.05016	0.04925	0.00760	(0.03481, 0.06551)

µ_difference: mean of (Max FE-CMC - Max FE-SO)

Test

Null hypothesis H_0: µ_difference = 0
Alternative hypothesis H_1: µ_difference ≠ 0

T-Value	P-Value
6.60	0.000

Figure F-10: Results of paired t-test comparing difference in maximum FE moment using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

Paired T-Test and CI: Min FE-CMC, Min FE-SO

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Min FE-CMC	42	0.00328	0.03744	0.00578
Min FE-SO	42	-0.00845	0.01370	0.00211

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for µ_difference
0.01173	0.03512	0.00542	(0.00079, 0.02268)

µ_difference: mean of (Min FE-CMC - Min FE-SO)

Test

Null hypothesis H_0: µ_difference = 0
Alternative hypothesis H_1: µ_difference ≠ 0

T-Value	P-Value
2.17	0.036

Figure F-11: Results of paired t-test comparing difference in minimum FE moment using inverse dynamics (CMC) and EMG-driven inverse dynamics (SO).

APPENDIX G: Knee Flexion Summary

One-Way Repeated Measures ANOVA Test

One-way ANOVA: 1st Peak versus Leg

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	$\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Leg	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Leg	1	1.105	1.105	0.03	0.857
Error	18	593.537	32.974		
Total	19	594.642			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5.74232	0.19%	0.00%	0.00%

Means

Leg	N	Mean	StDev	95% CI
ACLR	10	19.82	6.50	(16.01, 23.64)
Contralateral	10	20.29	4.87	(16.48, 24.11)

Pooled StDev = 5.74232

Figure G-1: Summary of one-way ANOVA test results comparing the 1st flexion peak during gait for ACLR and contralateral knees.

One-way ANOVA: Min Flex versus Leg

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Leg	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Leg	1	28.88	28.88	1.60	0.222
Error	18	324.54	18.03		
Total	19	353.42			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
4.24620	8.17%	3.07%	0.00%

Means

Leg	N	Mean	StDev	95% CI
ACLR	10	6.34	4.90	(3.52, 9.16)
Contralateral	10	3.94	3.47	(1.12, 6.76)

Pooled StDev = 4.24620

Figure G-2: Summary of one-way ANOVA test results comparing the minimum flexion angle during gait for ACLR and contralateral knees.

One-way ANOVA: 2nd Peak versus Leg

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Leg	2	ACLR, Contralateral

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Leg	1	1.131	1.131	0.09	0.763
Error	18	217.194	12.066		
Total	19	218.325			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.47366	0.52%	0.00%	0.00%

Means

Leg	N	Mean	StDev	95% CI
ACLR	10	63.75	3.75	(61.44, 66.06)
Contralateral	10	64.23	3.18	(61.92, 66.54)

Pooled StDev = 3.47366

Figure G-3: Summary of one-way ANOVA test results comparing the 2nd flexion peak during gait for ACLR and contralateral knees.

APPENDIX H: Enhanced Helen Hayes Marker Set

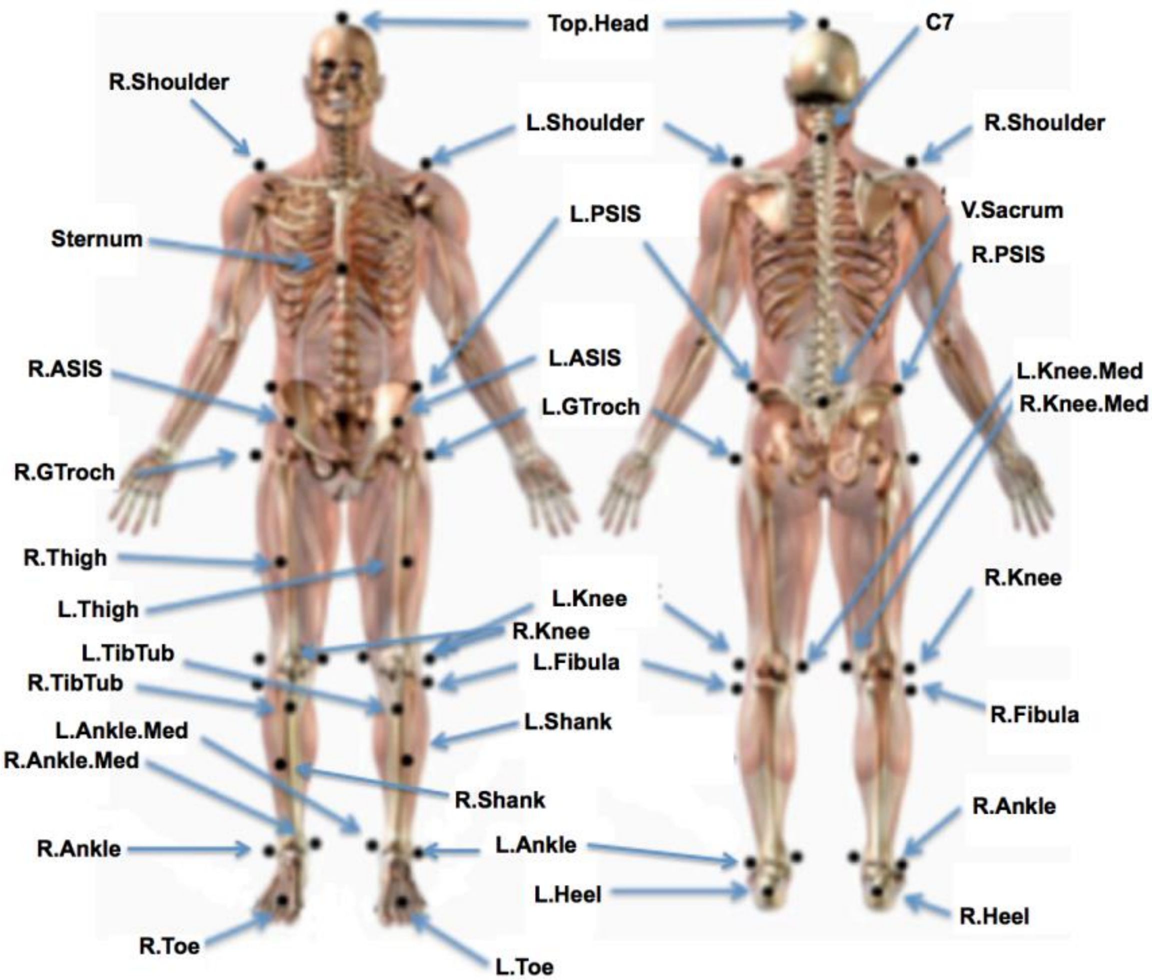

Figure H-1: Representation of the 32 markers used in an enhanced Helen Hayes marker set.

The marker set used for these experiments follows a modified Helen Hayes marker set. This is due to the OpenSim model used for this analysis not having arms and additional markers placed on the knees and hips for more accurate kinematic data.

APPENDIX I: Cycling Power Output Calculations

Power output calculations for the cycling were based on crank length (172 mm), crank angle (Fig. 2.5), and instrumented load cell forces (Fig. I-1). For each crank cycle analyzed, the moment at each time point during the crank cycle was computed (Eq. I-3). The power of each leg was computed by multiplying the average moment over a crank cycle by the cadence (Eq. I-4). The average power of both legs for each cycle was summed.

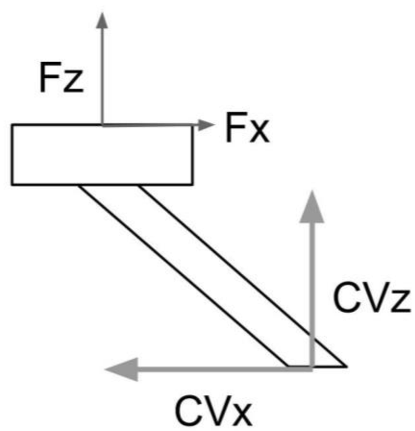

Figure I-1: Depiction of the Cortex coordinate system used for load cell (Fx, Fz) forces and crank vector (CVx, CVz) orientation.

$$CVx = -.172 \times \sin(CrankAngle)$$ Eq. I-1

$$CVz = .172 \times \cos(CrankAngle)$$ Eq. I-2

$$Moment = Fz \times CVx + Fx \times CVz$$ Eq. I-3

$$Power\ (Watts) = \frac{70\ RPM \times 2\pi\ rad}{60\ \text{sec}} \times Moment_{Ave}$$ Eq. 1-4